The Incredible Lightness of Water Vapor

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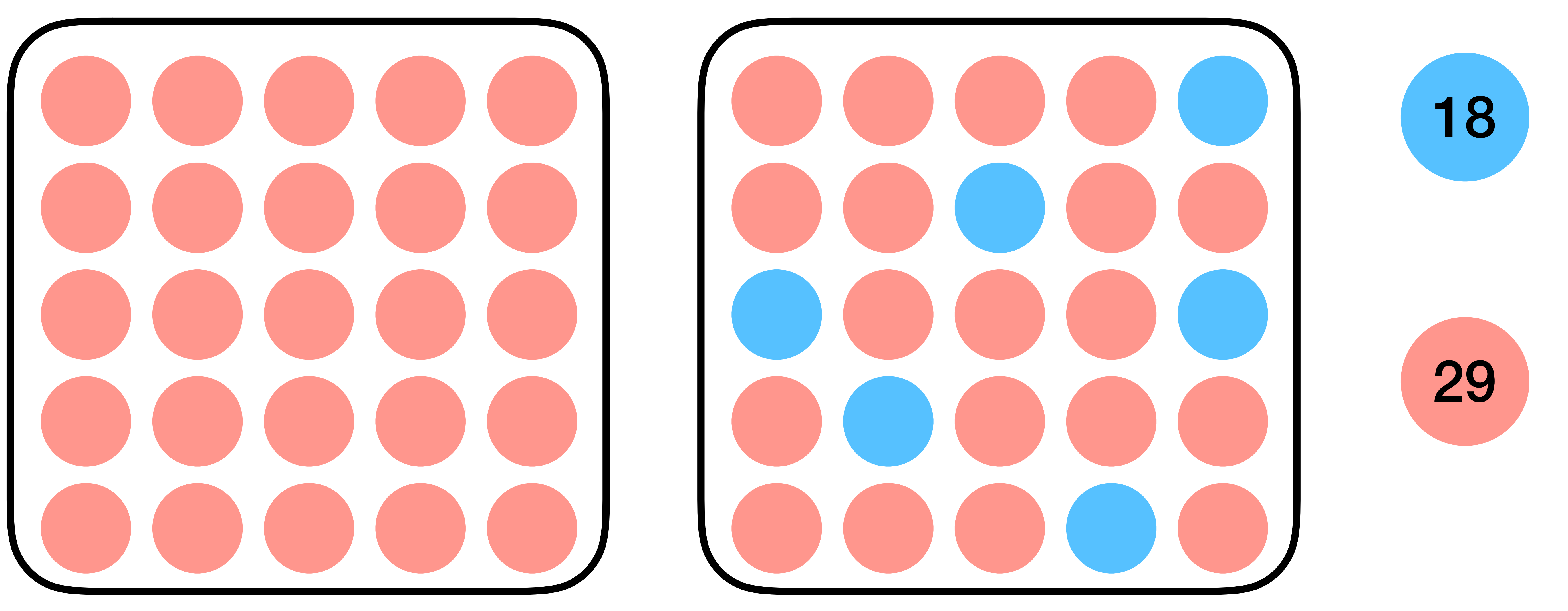
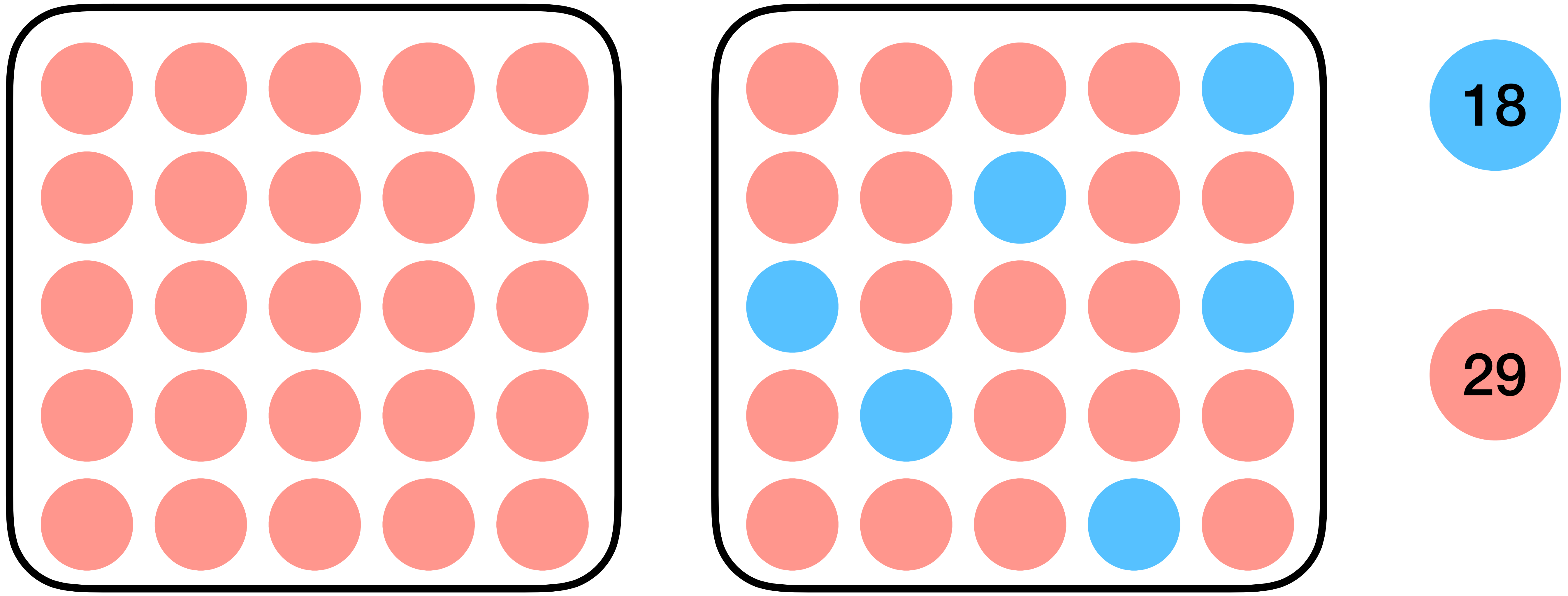
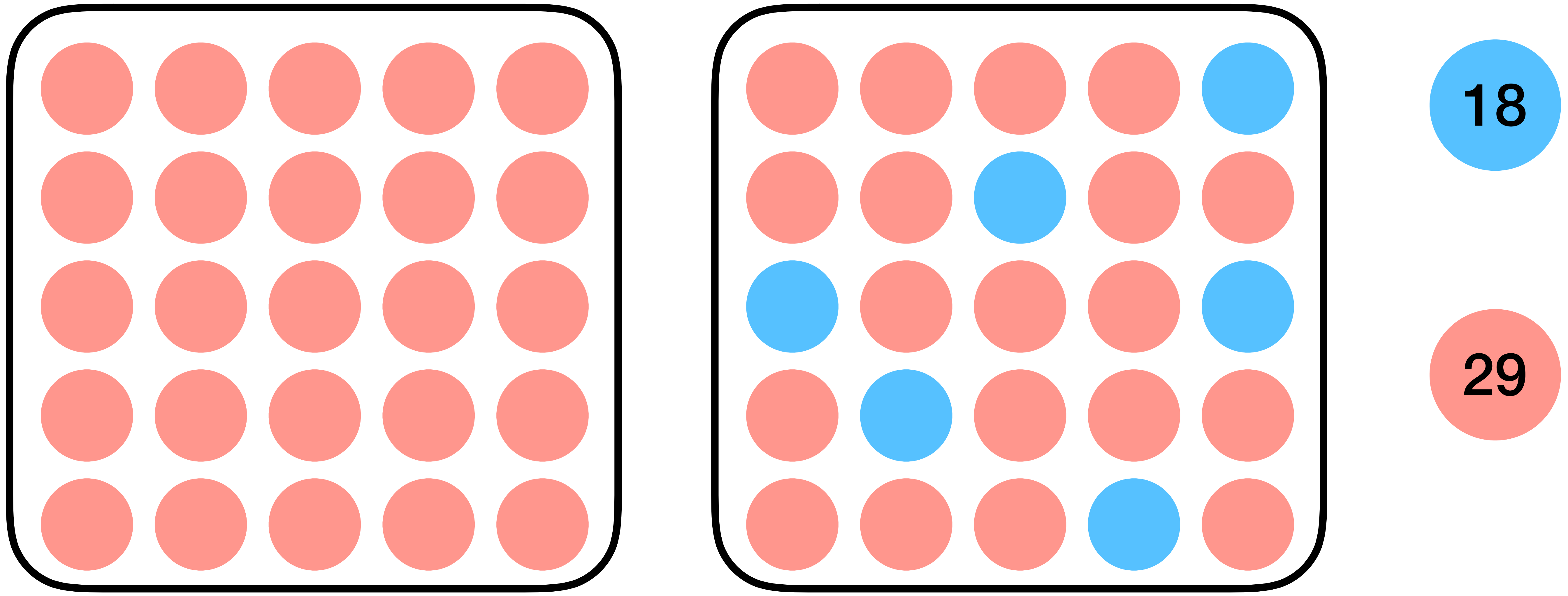


1. Greenhouse effect
2. Latent heat release in convection
3. The lightness of water vapor

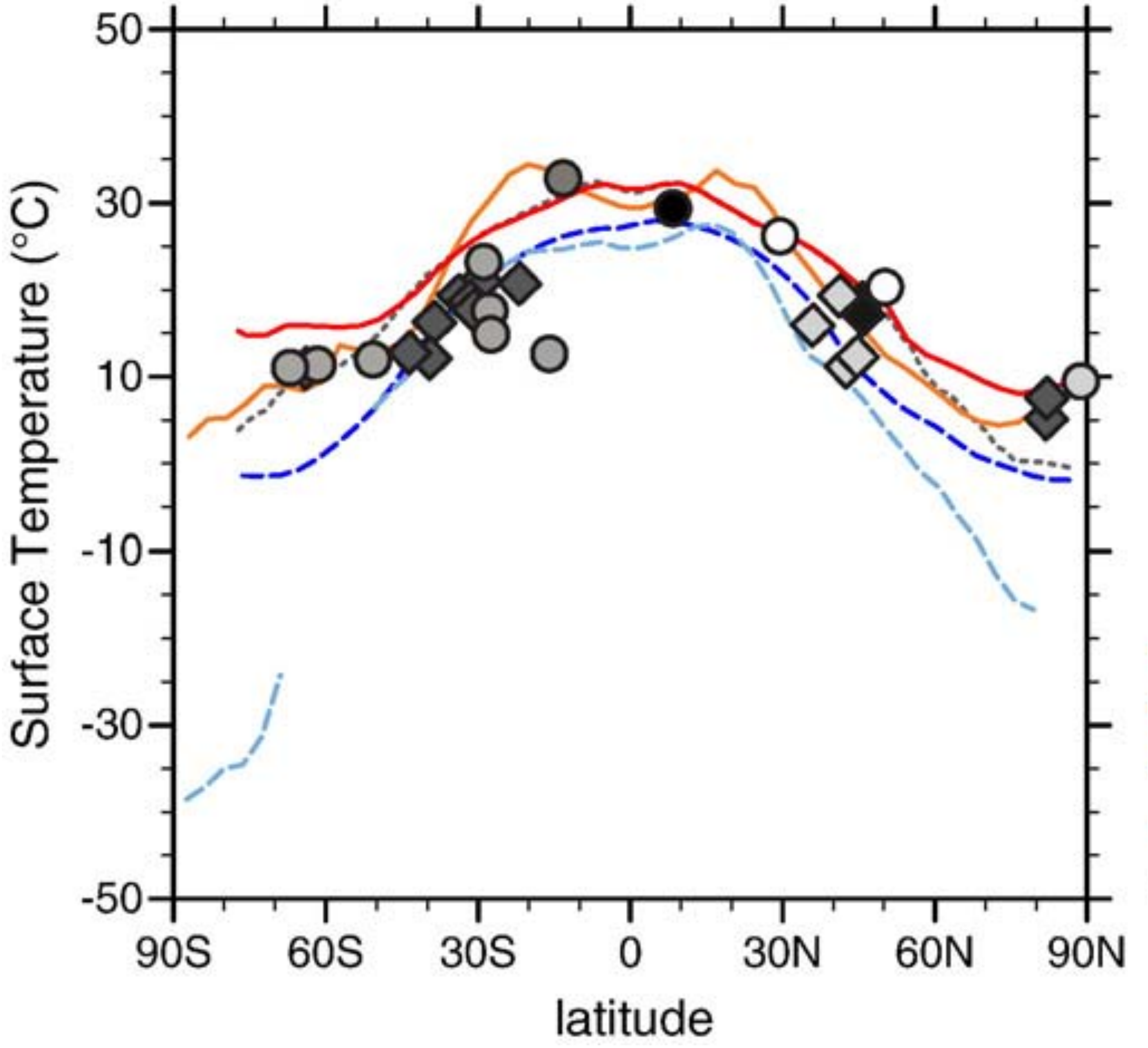


The lightness of water vapor stabilizes Earth's climate: 1D, 2D, and 3D models

1. Greenhouse effect
2. Latent heat release in convection
3. The lightness of water vapor



Strongly reduced equator-to-pole temperature gradient in the past warm climates



Markers: Paleo proxies
Blue dashed: Reference SST
Other lines: GCM simulations of paleo SSTs

Speelman et al. 2010

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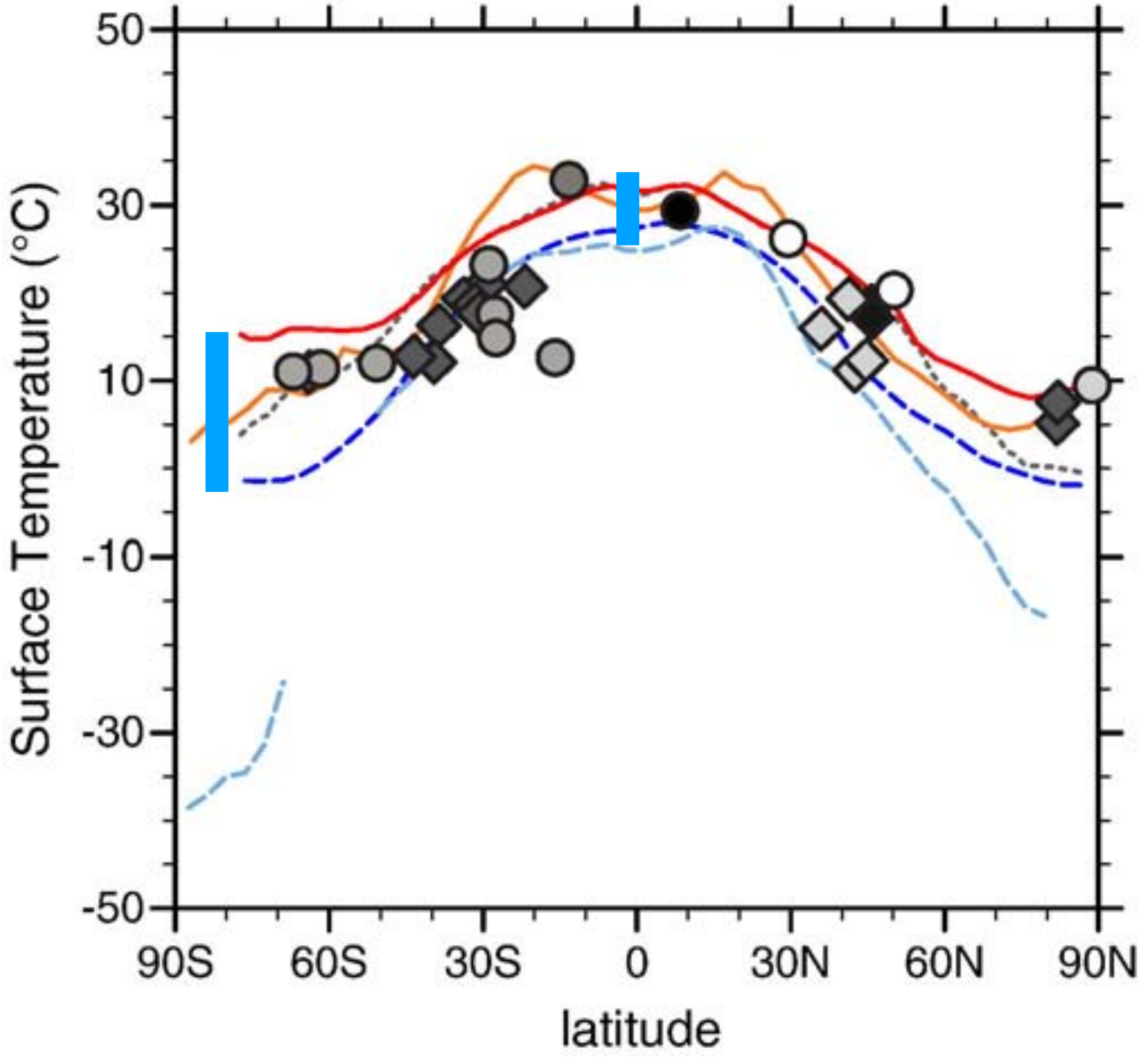

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Speelman et al. 2010

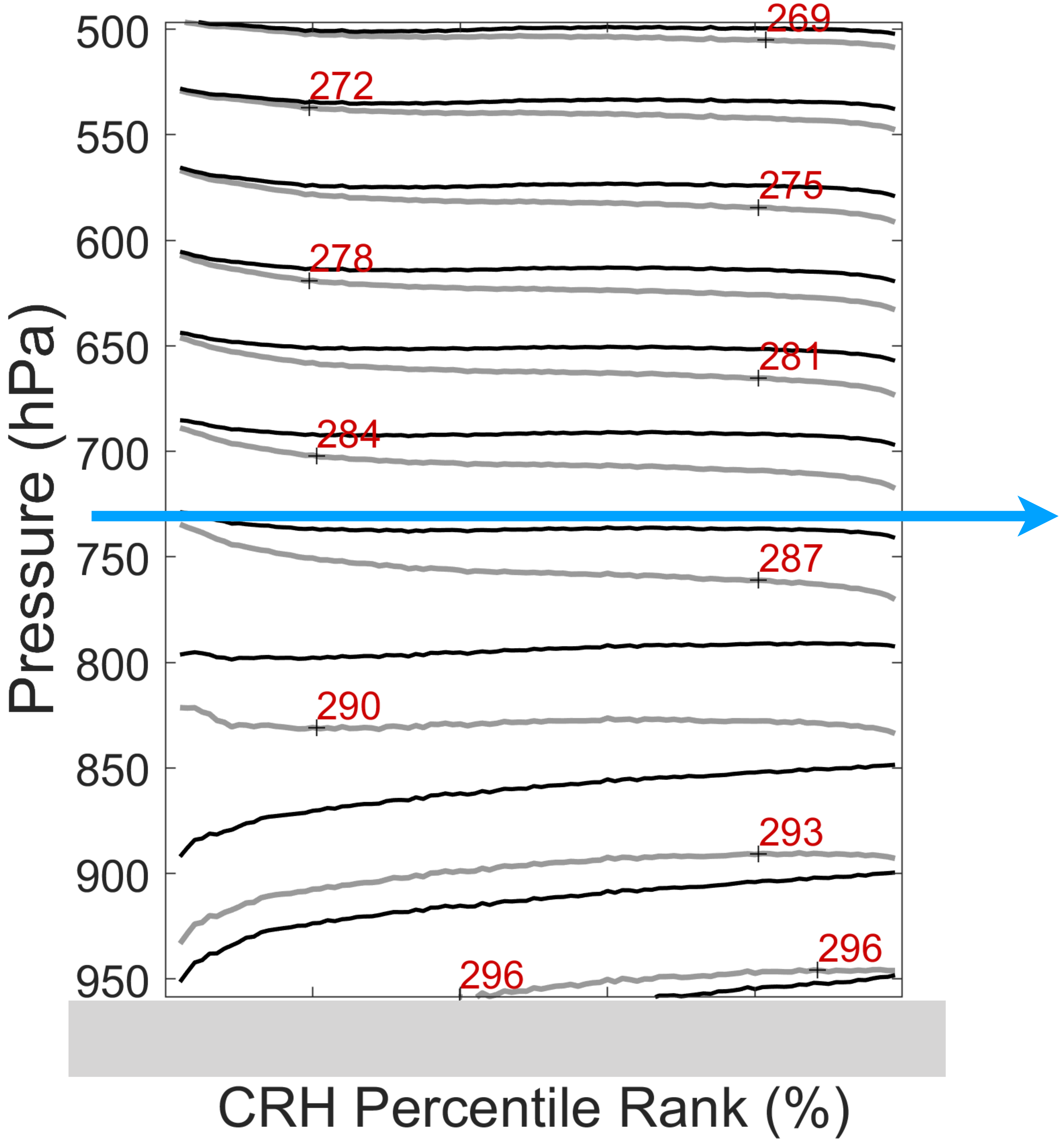
Strongly reduced equator-to-pole temperature gradient in the past climates

Markers: Paleo proxies

Why is tropical climate so stable?

Other lines: GCM simulations of paleo SSTs

Horizontal buoyancy gradient is negligible in the tropical free troposphere. However, there ***is*** significant temperature gradient.

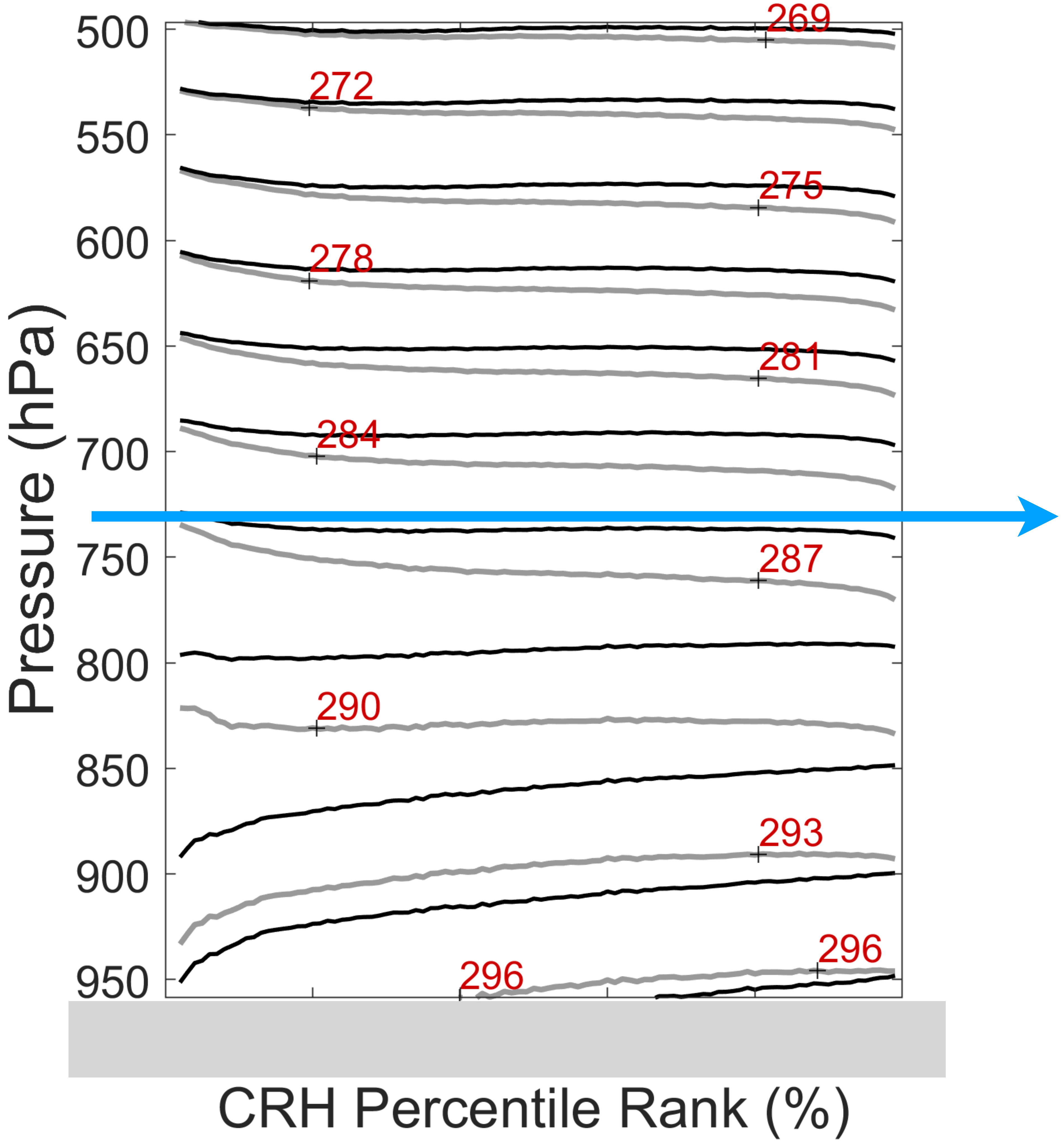


Black: buoyancy; gray: temperature
CRH = Column Relative Humidity

NASA AIRS data; 2°S to 2°N

No forces can balance horizontal buoyancy gradient in the tropical free troposphere.

Horizontal buoyancy gradient is negligible in the tropical free troposphere. However, there **is** significant temperature gradient.



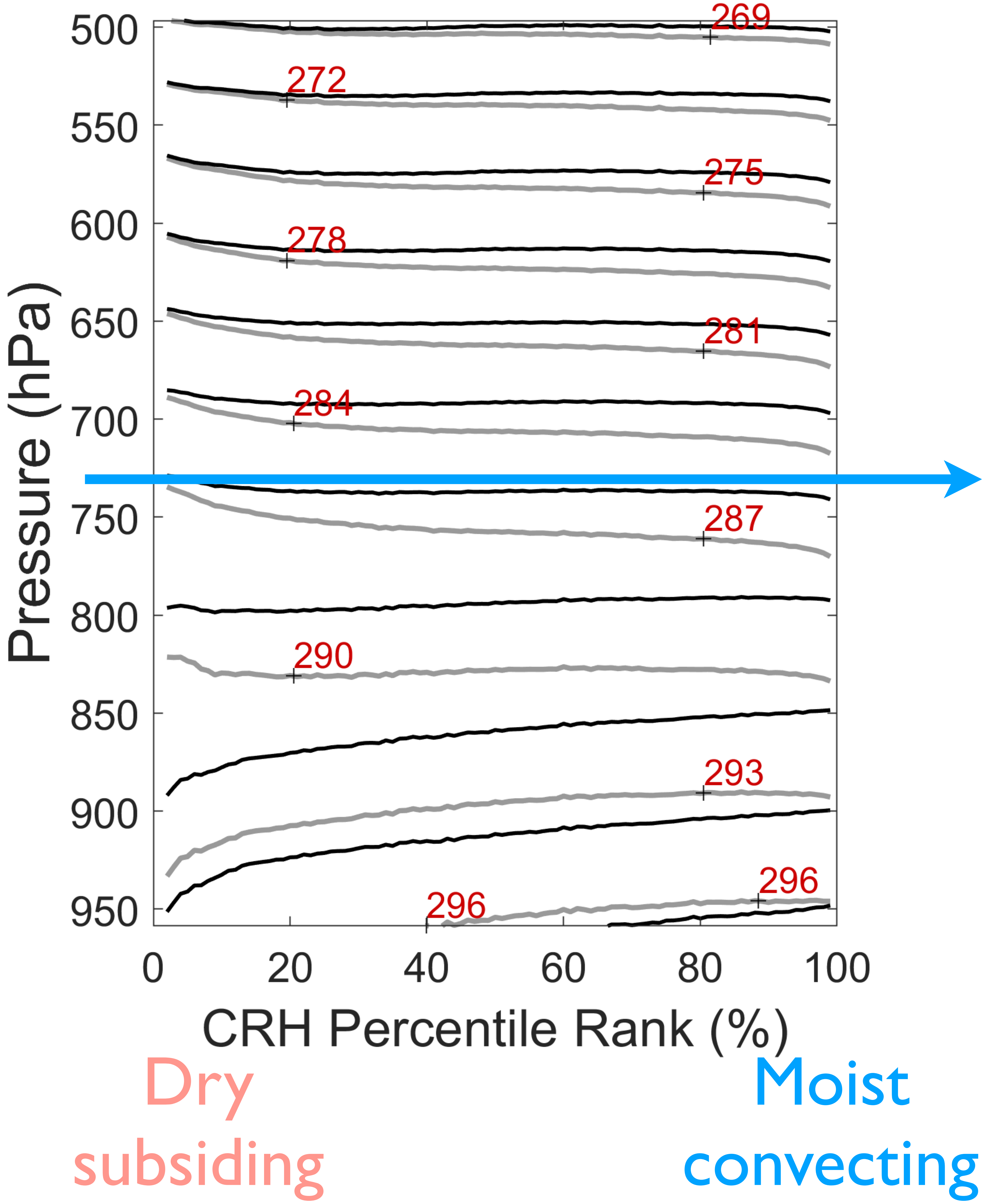
Where are the precipitating moist columns?

Black: buoyancy; gray: temperature

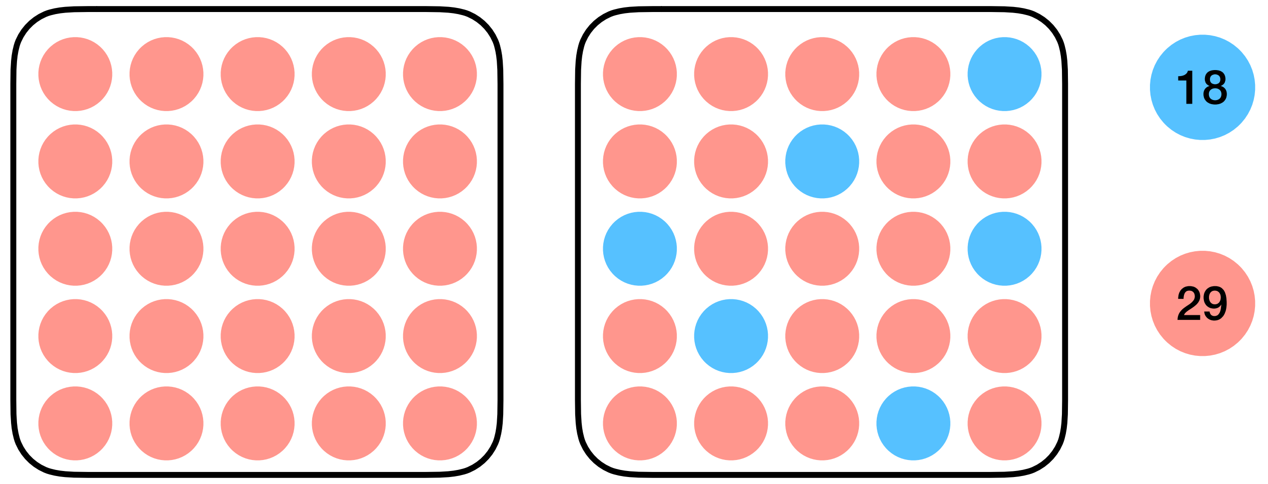
CRH = Column Relative Humidity

NASA AIRS data; 2°S to 2°N

Cold air rises!



$\Delta T \sim 2K$



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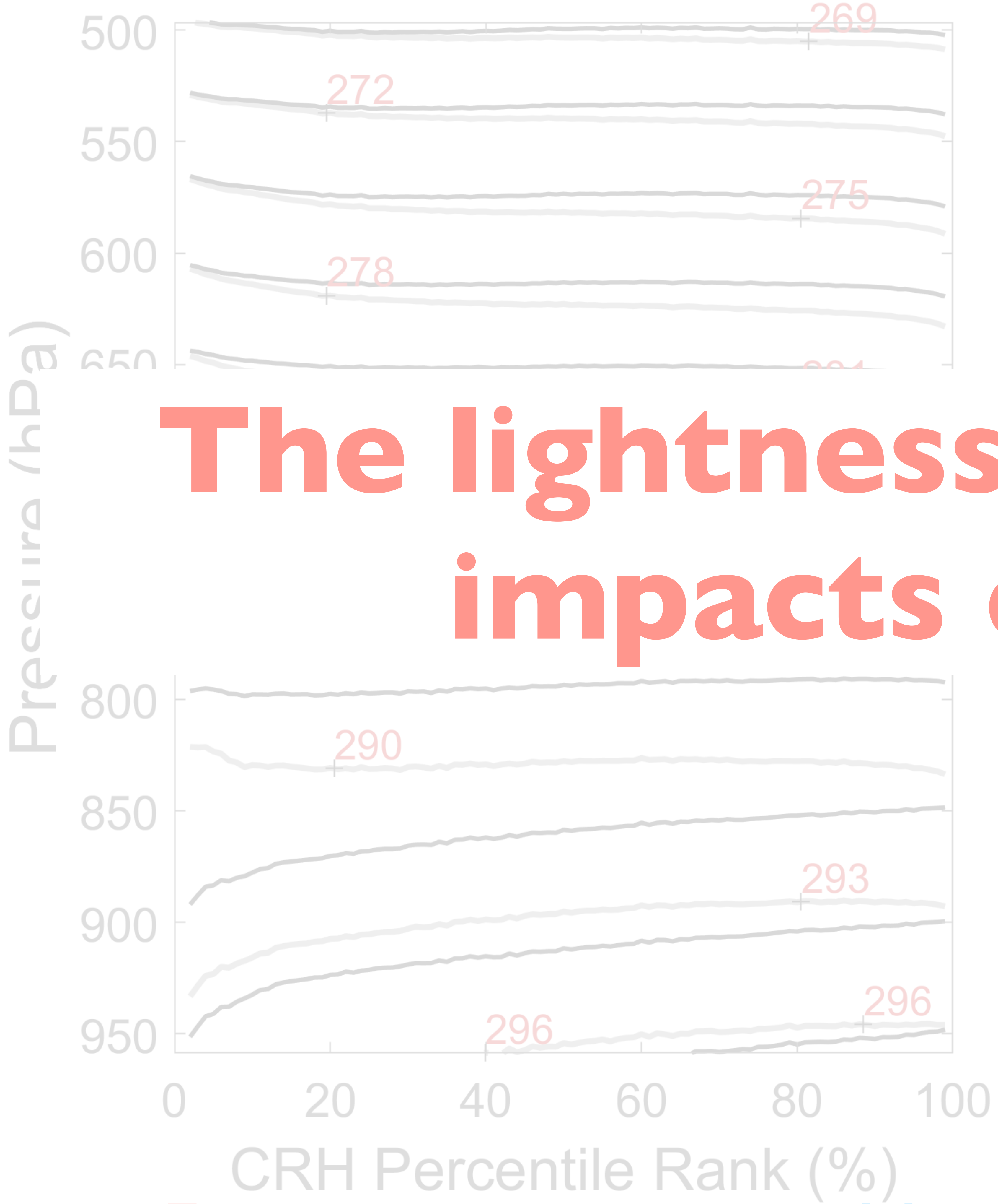
Horizontal buoyancy gradient is negligible in the tropical free troposphere. However, there is significant temperature gradient.



Dry subsiding

Moist convecting

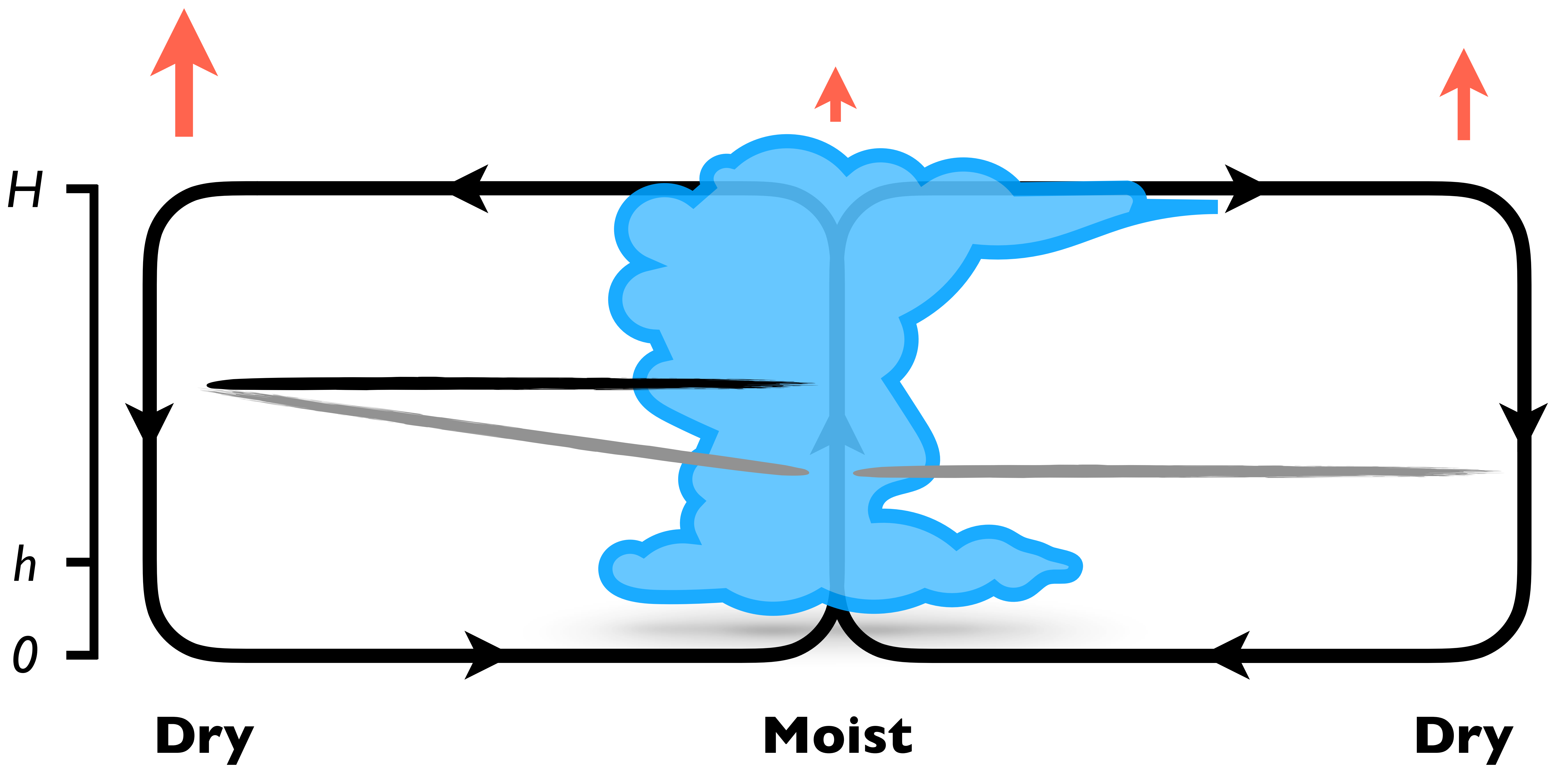
The lightness of water vapor has profound impacts on the thermal structure

Black: buoyancy; gray: temperature

CRH = Column Relative Humidity

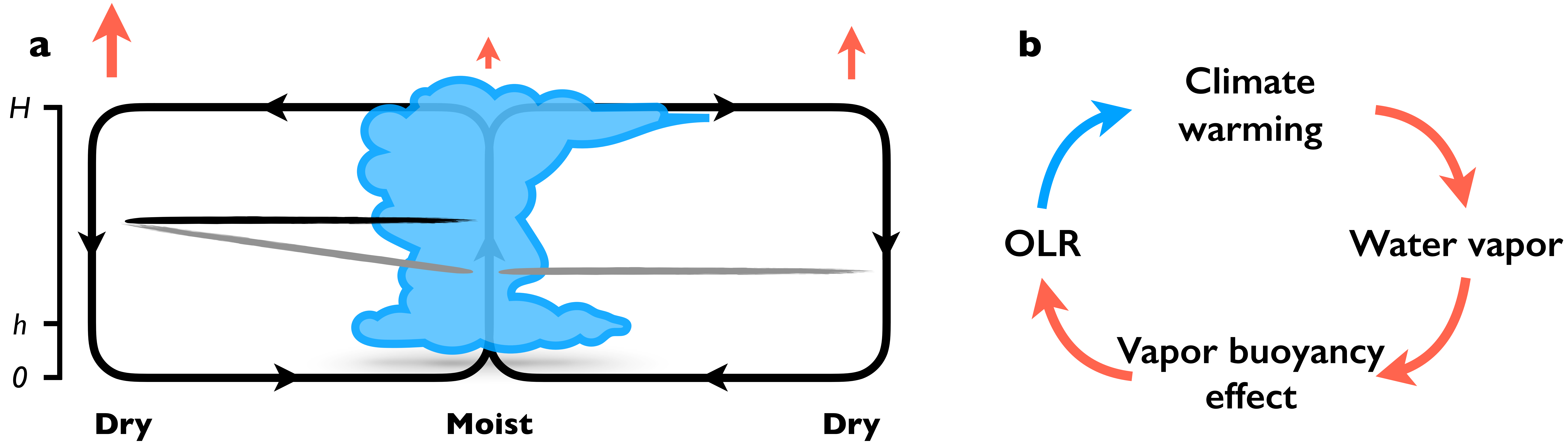
NASA AIRS data; 2°S to 2°N

The lightness of water vapor can increase OLR



Two stand-alone atmospheres with same SST; no/weak rotation
The circulation corresponds to Hadley/Walker circulation

This effect increases with warming—a negative climate feedback



Key ingredients:
1) overturning circulations (moist and dry columns);
2) weak B gradients but significant T gradients

1D: imposed
2D: self-emerged
3D: self-emerged

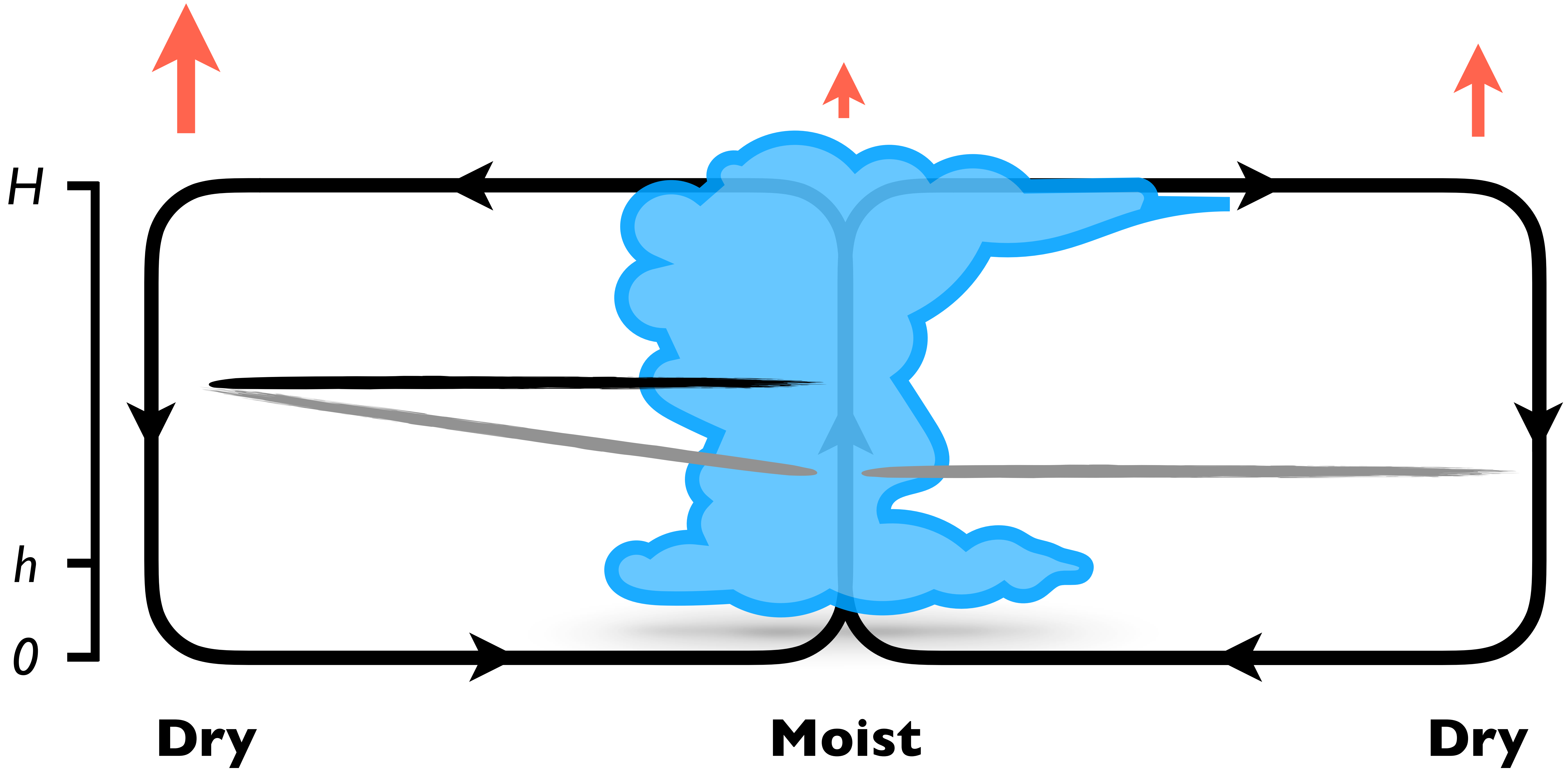
A few important numbers

Radiative forcing due to doubling CO_2 is about **3 - 4 W/m²**

The strength of surface albedo feedback and cloud feedback is about **0.1 W/m²/K**

We will compare the radiative effect of the vapor buoyancy to the above numbers

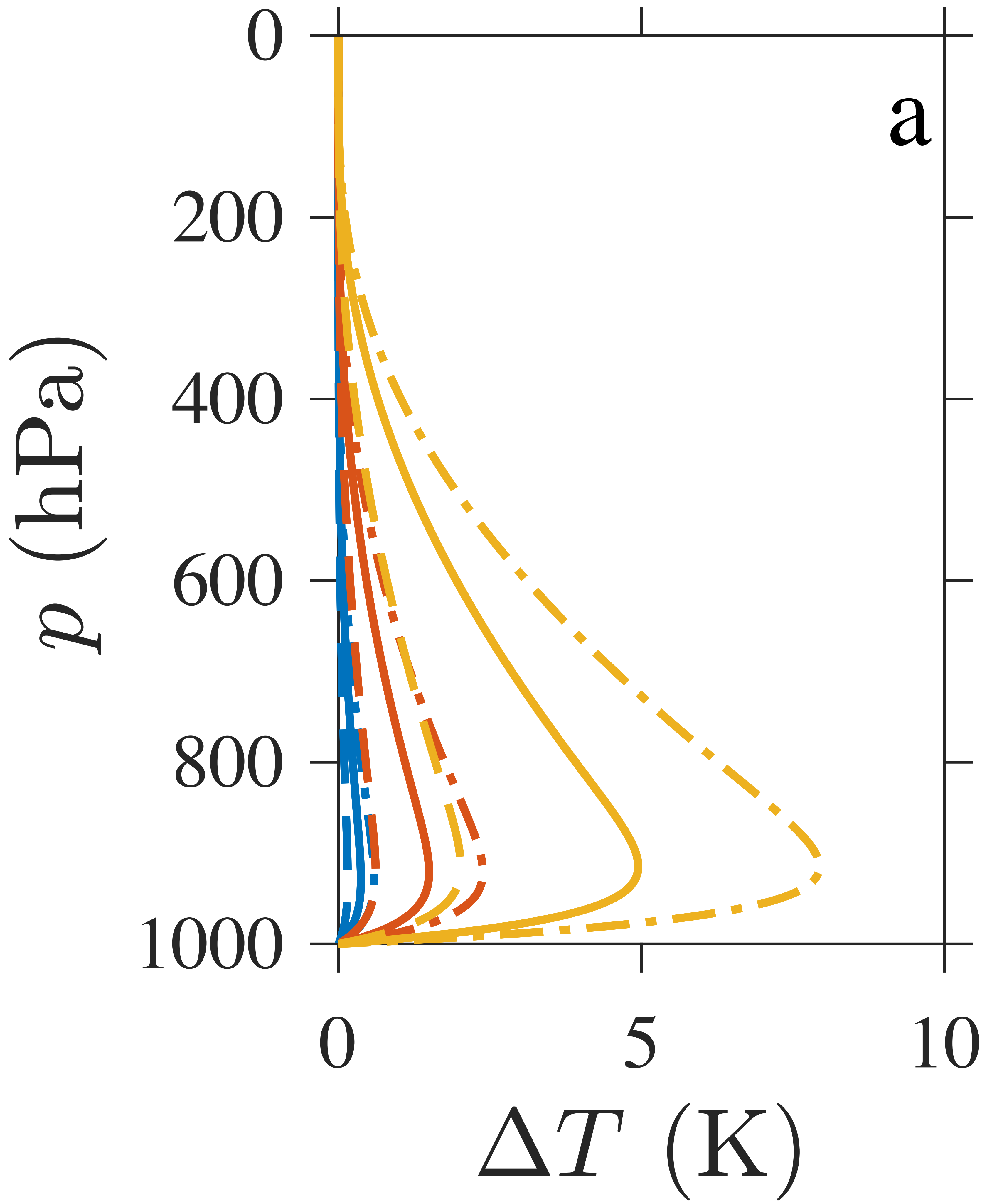
The lightness of water vapor can increase OLR



$$T_{dry} > T_{moist} = T_{dry,noVB}$$

$$\Delta T = T_{dry} - T_{dry,noVB} = T_{dry} - T_{moist}$$

ΔT increases with surface temperature and moisture contrasts



$$\Delta T_{WBG} = T_m \left(\frac{1}{\varepsilon} - 1 \right) \underbrace{(r_m - r_d)}_{\text{moisture contrast}}$$

280 K

300 K

320 K

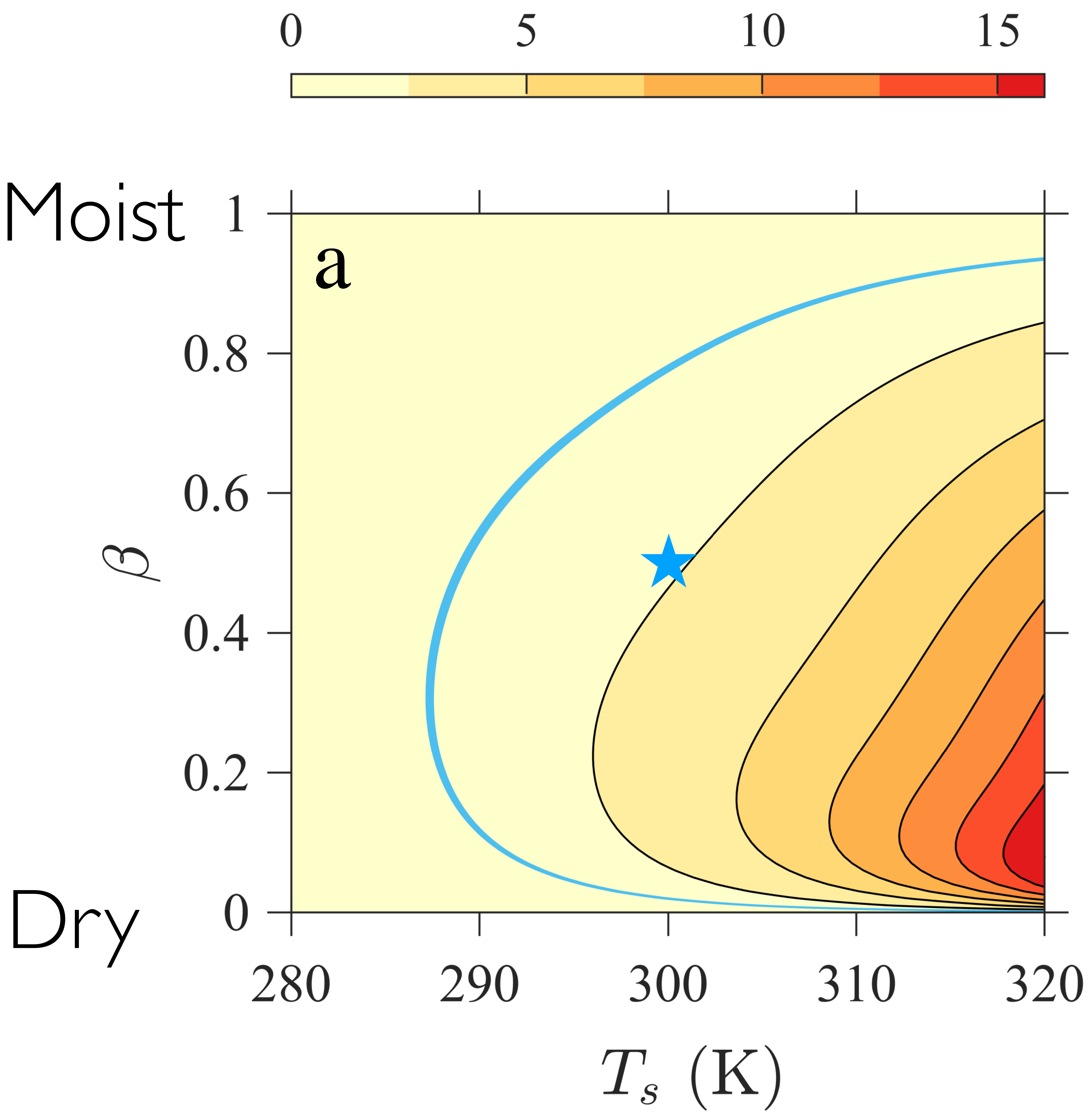
dot-dashed: $\beta = 0.2$

solid: $\beta = 0.5$

dashed: $\beta = 0.8$

Order-of-magnitude calculations using a 1D model

Yang and Seidel 2019: 10.31223/osf.io/ha9sx



$$\Delta OLR \sim \underline{2 - 4\ W/m^2}$$

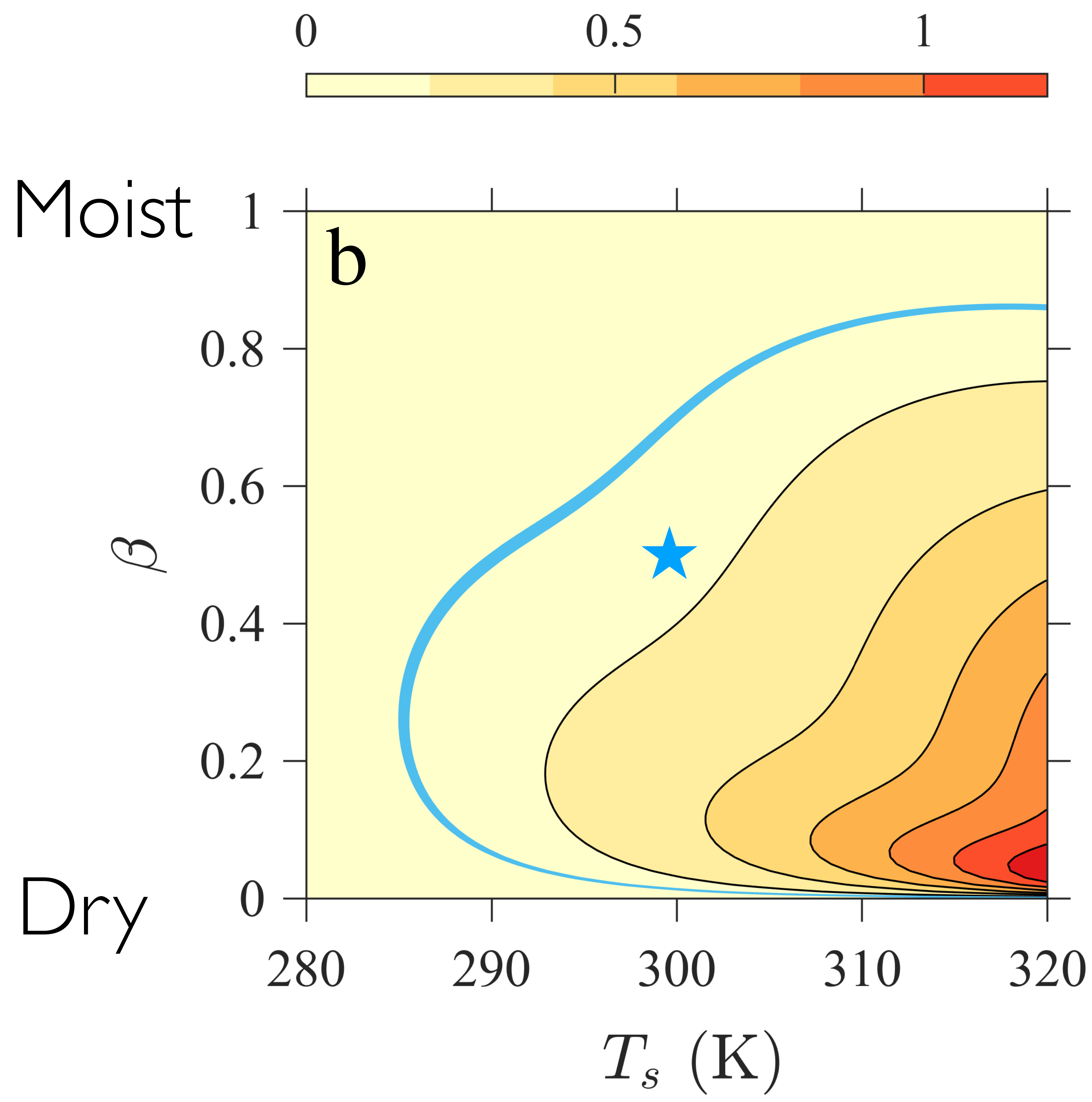
Similar to doubling CO_2

This effect is *small* at both the *moist and dry limits*

$$\beta = \frac{\text{moisture in dry column}}{\text{moisture in moist column}}$$

Order-of-magnitude calculations using a 1D model

Yang and Seidel 2019: 10.31223/osf.io/ha9sx

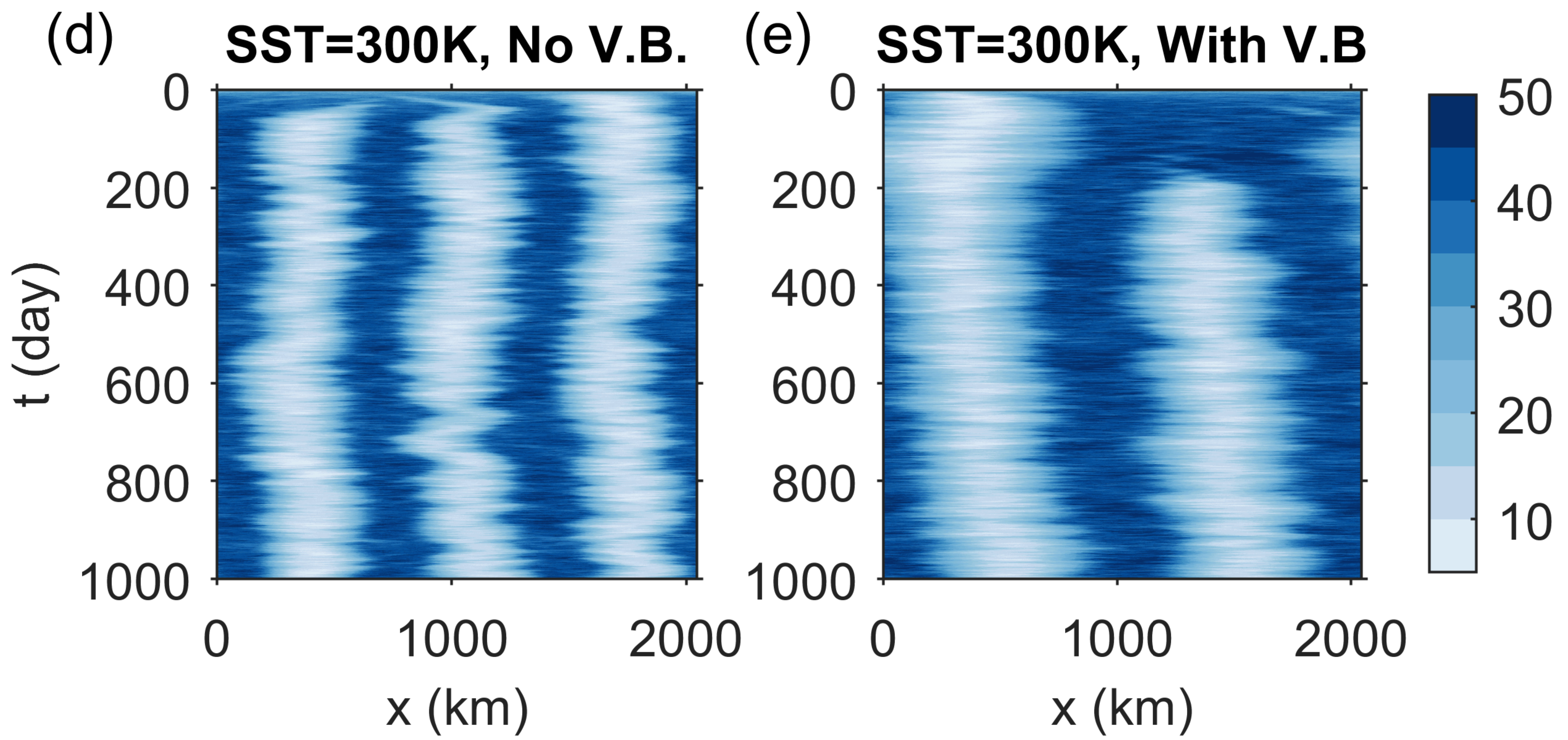


$$d\Delta OLR/dT_s \sim \underline{0.2\ W/m^2/K}$$

Similar to cloud or surface albedo feedbacks

This effect is *small* at both the *moist and dry limits*

Moist and dry patches are simulated in 2D cloud-resolving model (CRM) simulations



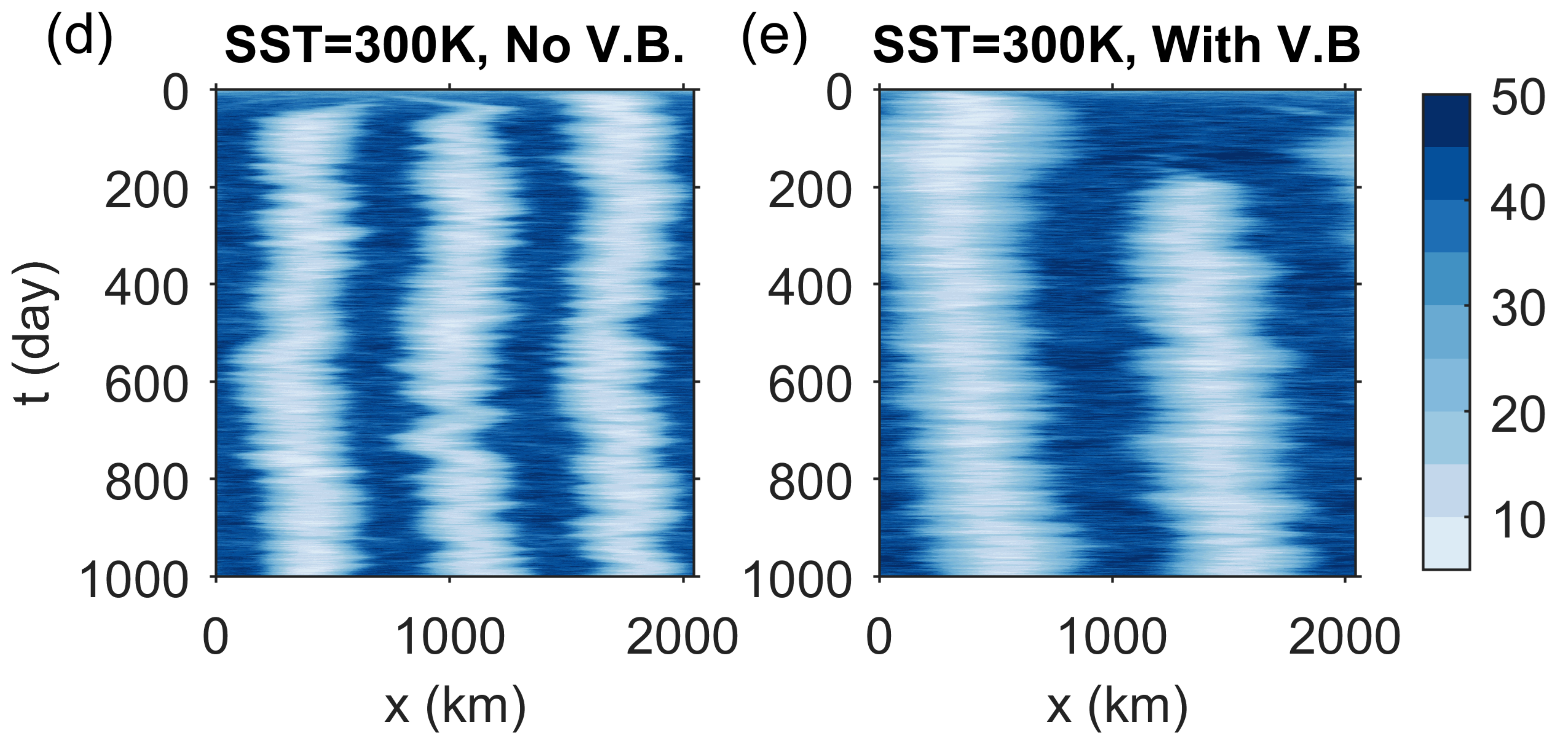
Color shading: Precipitable water

There is no rotation

Left: no vapor buoyancy

right: with vapor buoyancy

Moist and dry patches are simulated in 2D cloud-resolving model (CRM) simulations



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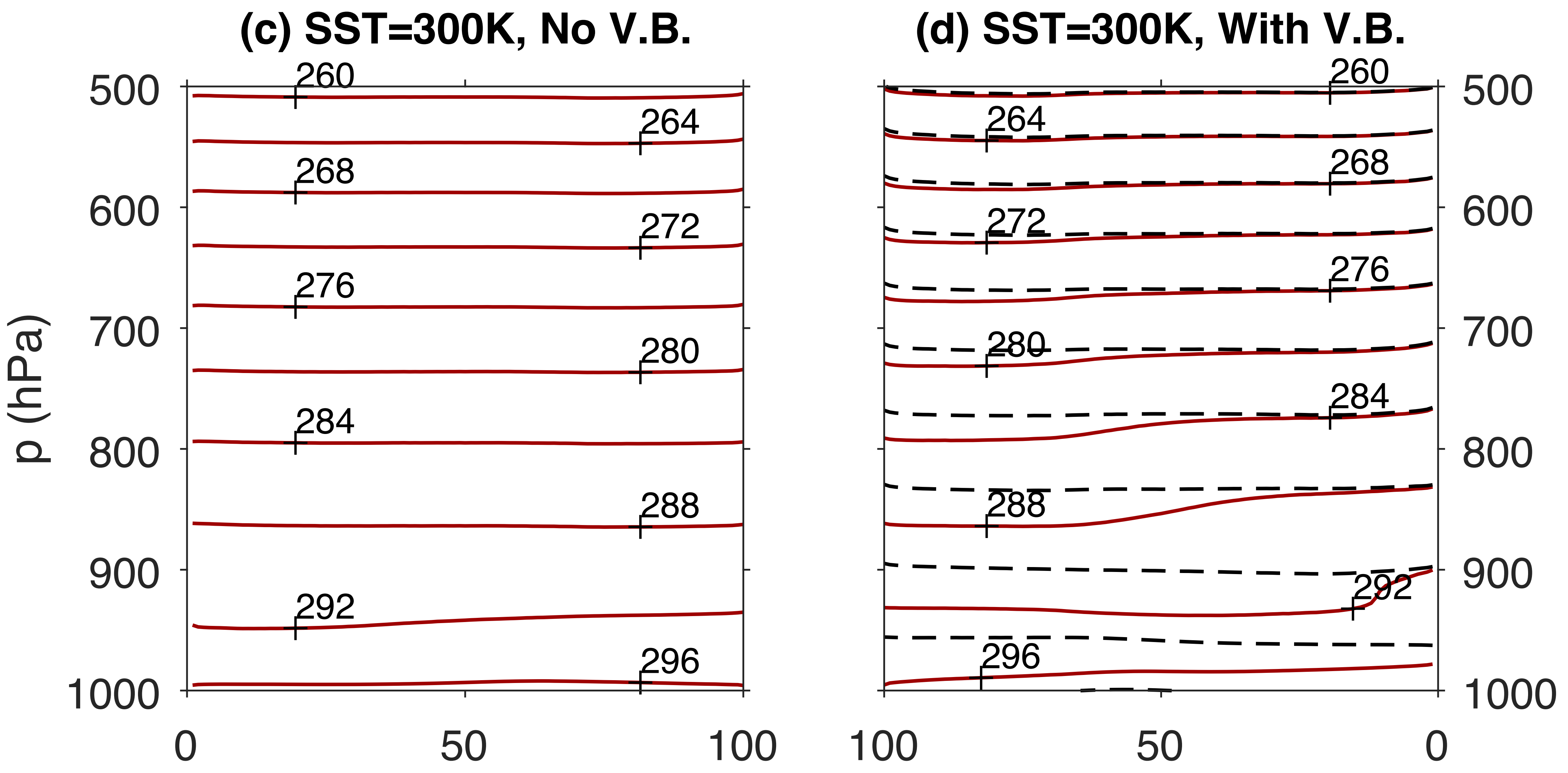


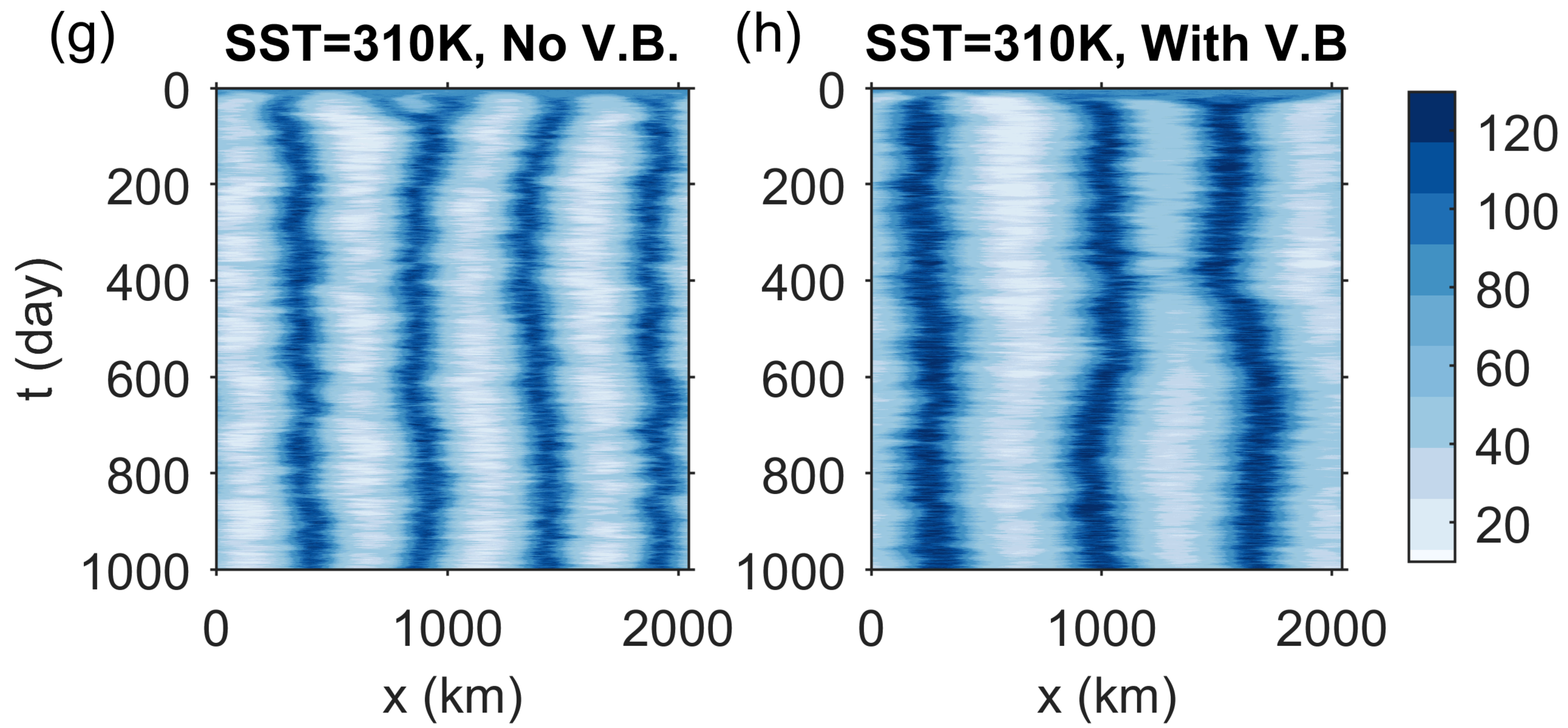
WBG and △T self-emerge!

$$\Delta T \sim 2K$$

Red: Temperature

Black: Buoyancy

Moist and dry patches are simulated in 2D cloud-resolving model (CRM) simulations



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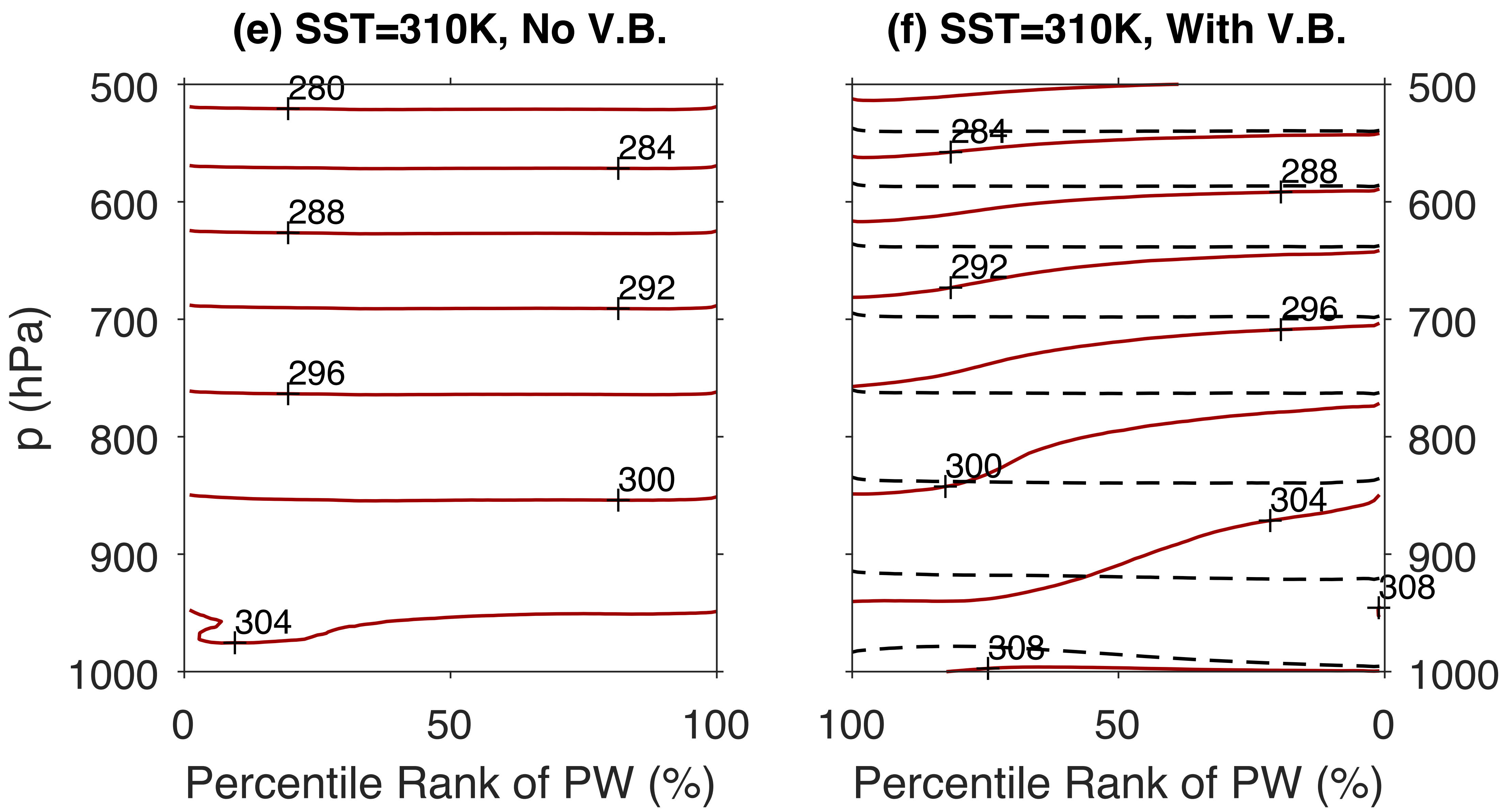


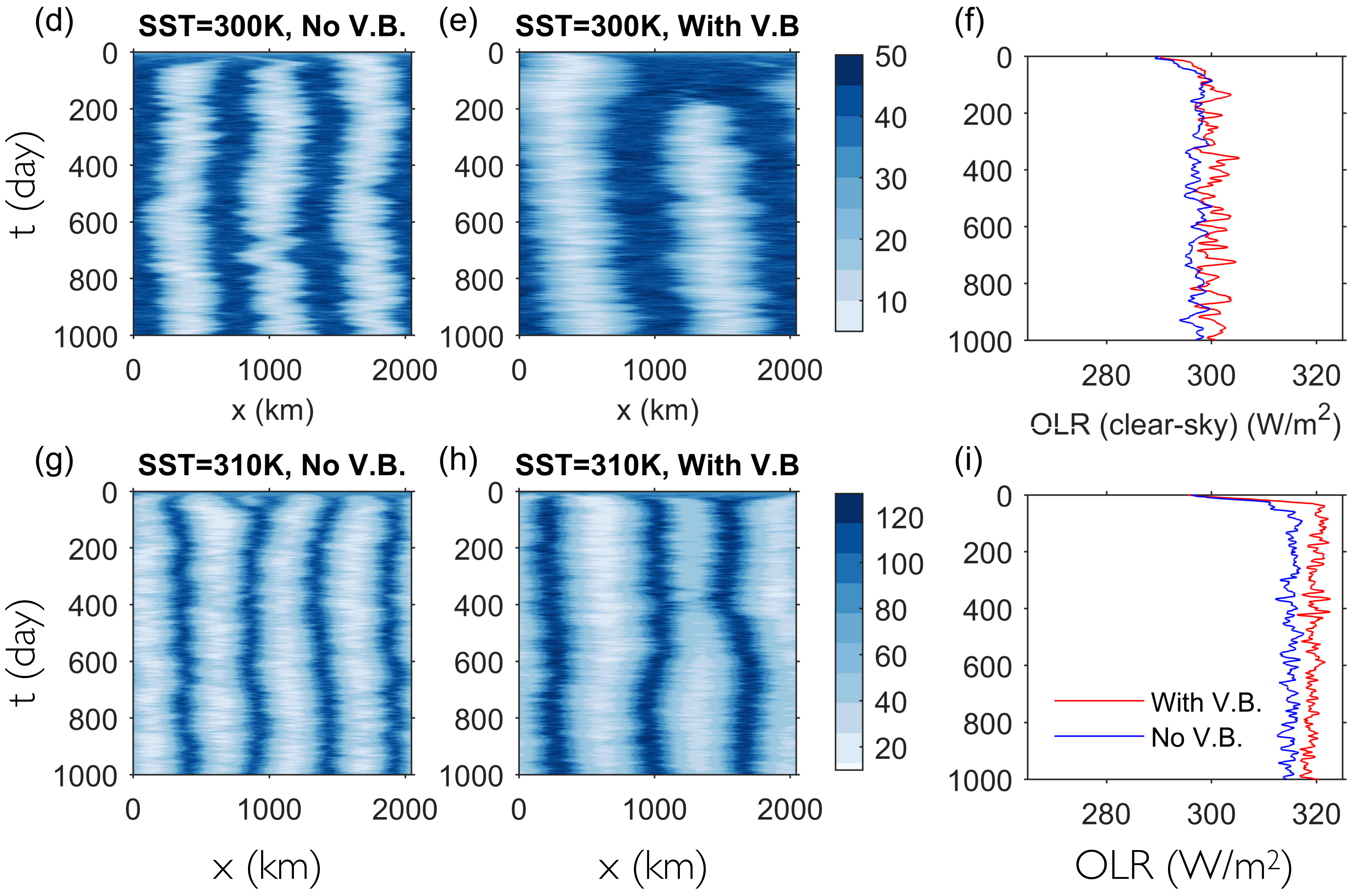
WBG and △T self-emerge!

$$\Delta T \sim 4K$$

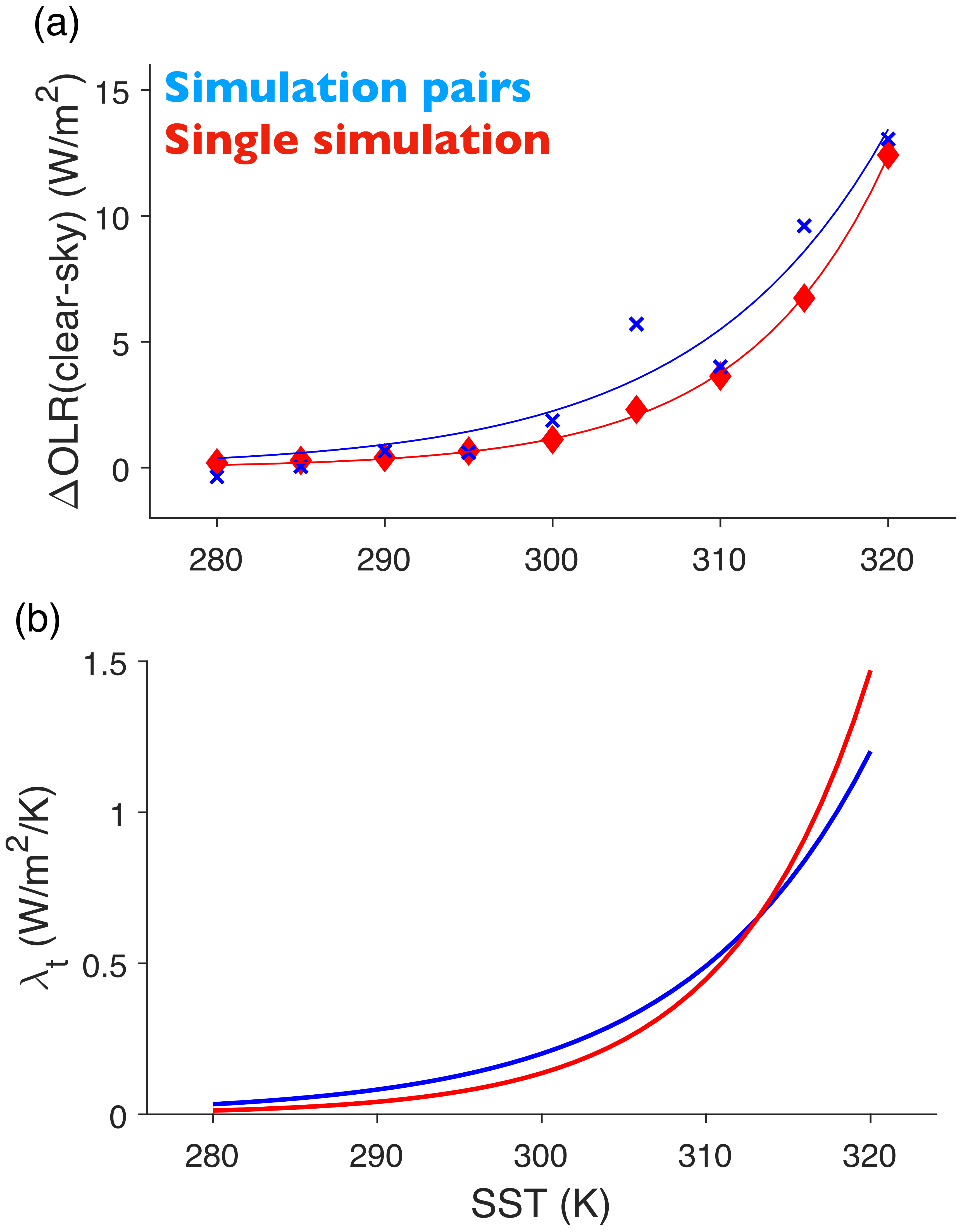
Red: Temperature

Black: Buoyancy

The lightness of water vapor increases OLR
This effect increases with warming, a negative feedback



2D CRM results confirm our 1D results



Radiative effect is about 2 W/m^2

It increases exponentially

Similar to $2XCO_2$

Feedback parameter is about 0.2 W/m^2/K

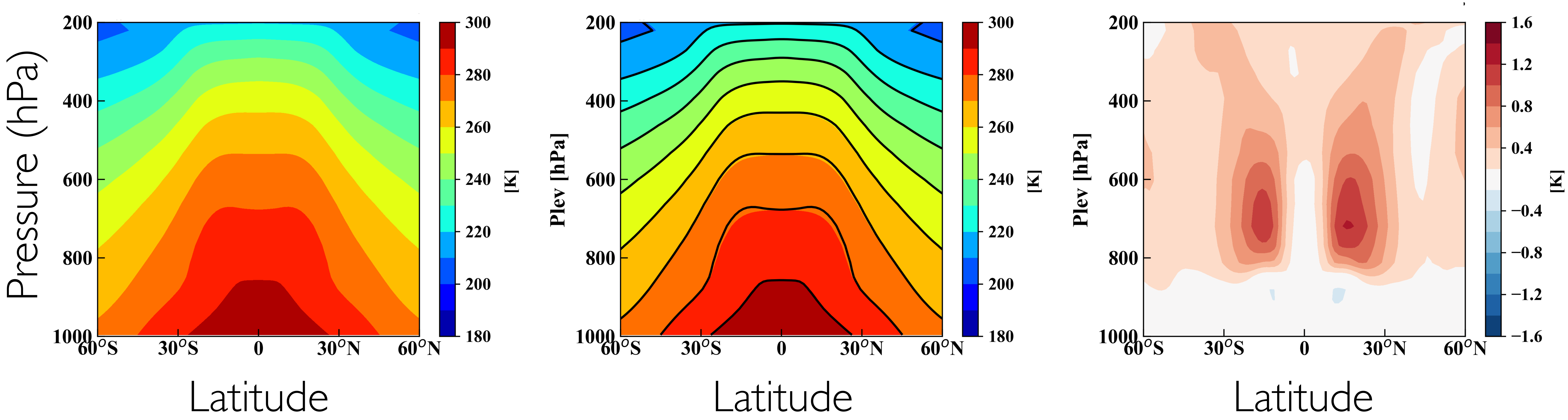
It also increases with warming.

Similar to cloud or surface albedo feedbacks

Seidel and Yang, 2019 (to be submitted)

We further test the hypothesis in a 3D GCM

With vapor buoyancy Temperature − No vapor buoyancy Temperature = $\Delta T \sim O(1.5\ K)$

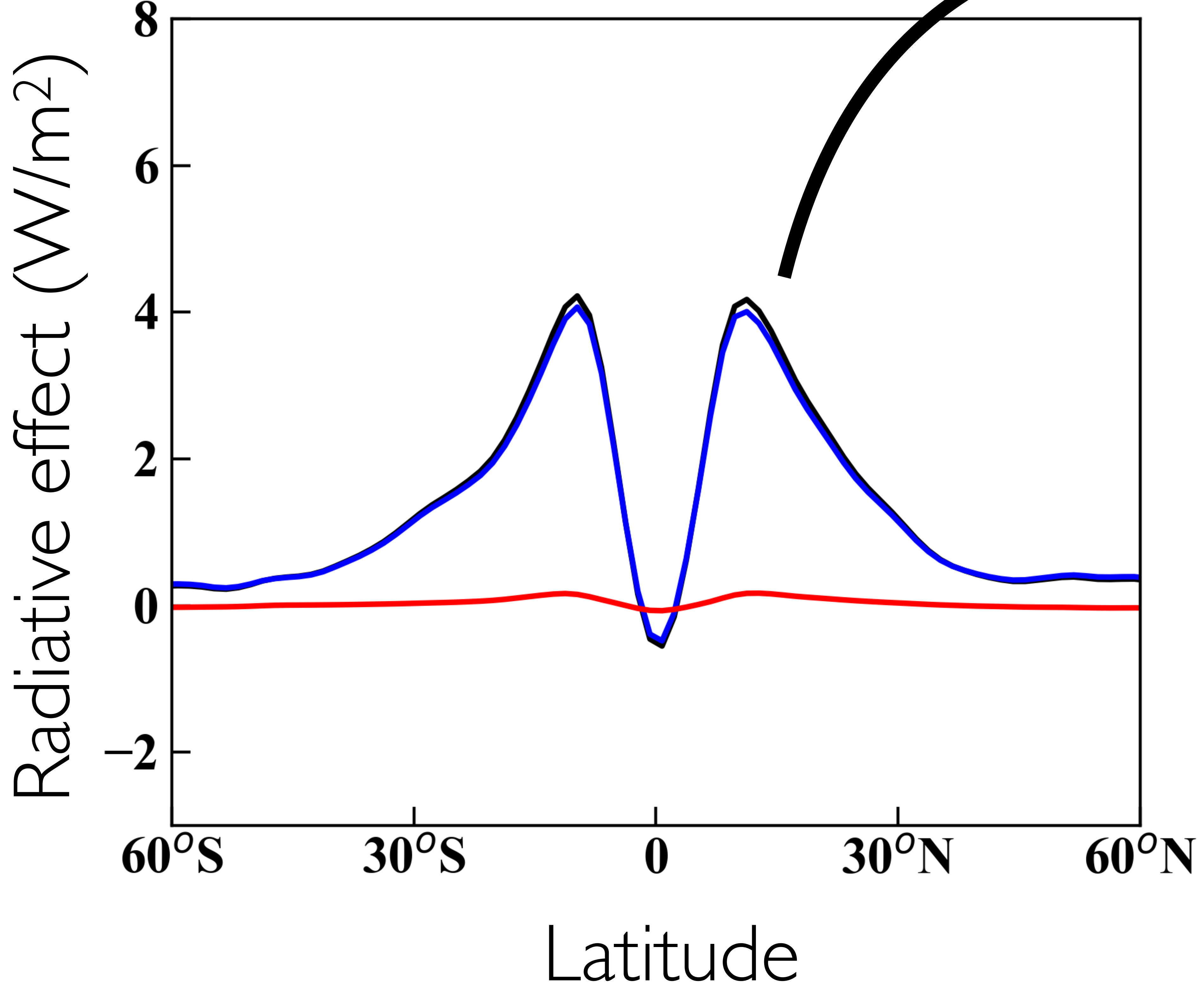


GFDL AM2 model; 20-yr simulations with fixed SSTs;
Last 5 years are analyzed.

The radiative effect peaks in the tropics

The max value is about 5 W/m^2

The global-averaged value is about 1.5 W/m^2



$$\Delta OLR \sim O(5\ W/m^2)$$

The radiative effect peaks in the tropics

The max value is about 5 W/m2

The global-averaged value is about 1.5 W/m2

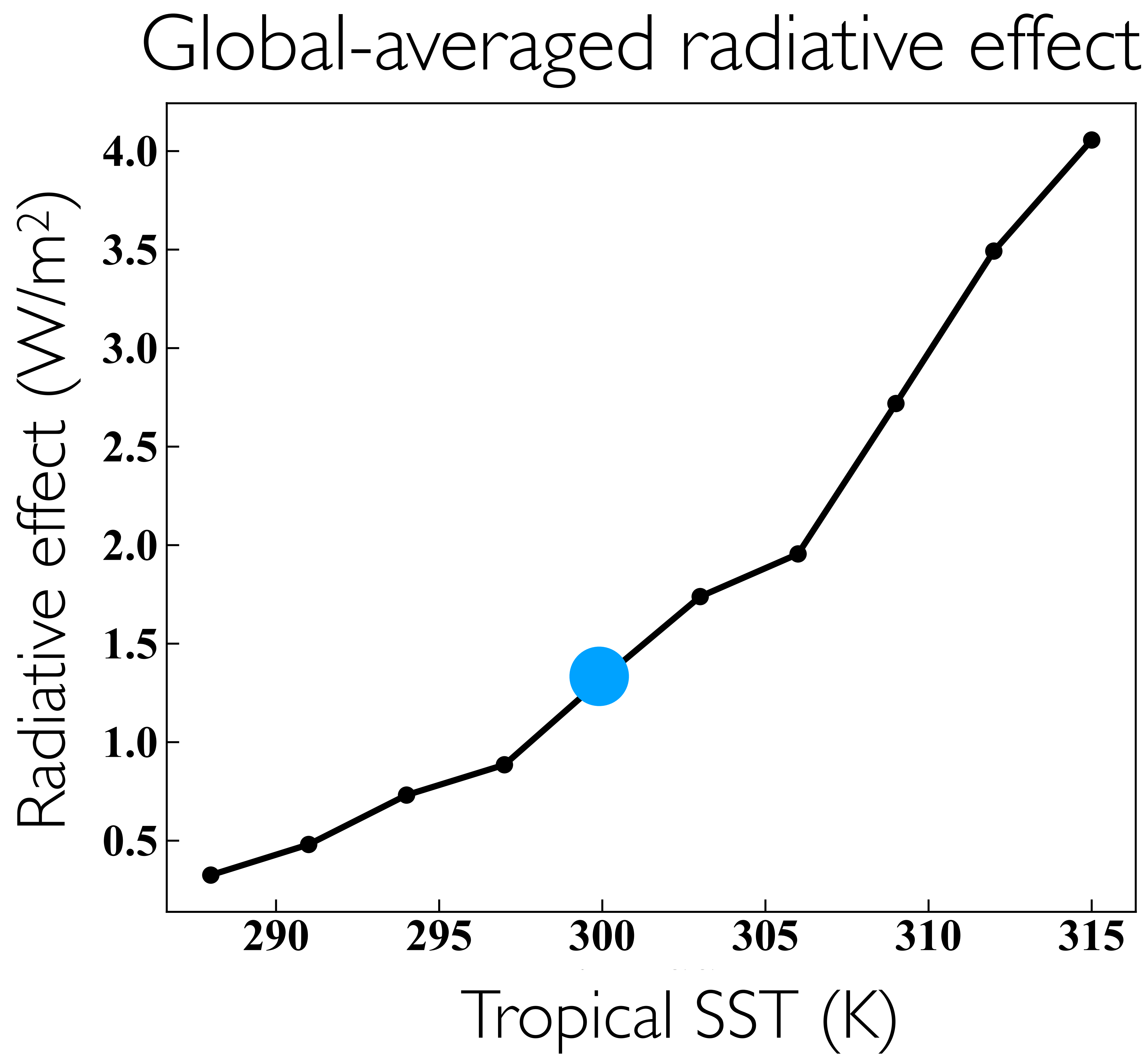
Effectively stabilize tropical climate!

$\Delta OLR \sim O(5\ W/m^2)$

3D GCM simulations confirm our hypothesis

The global-averaged radiative effect is about 1.5 W/m²

This effect increases with warming

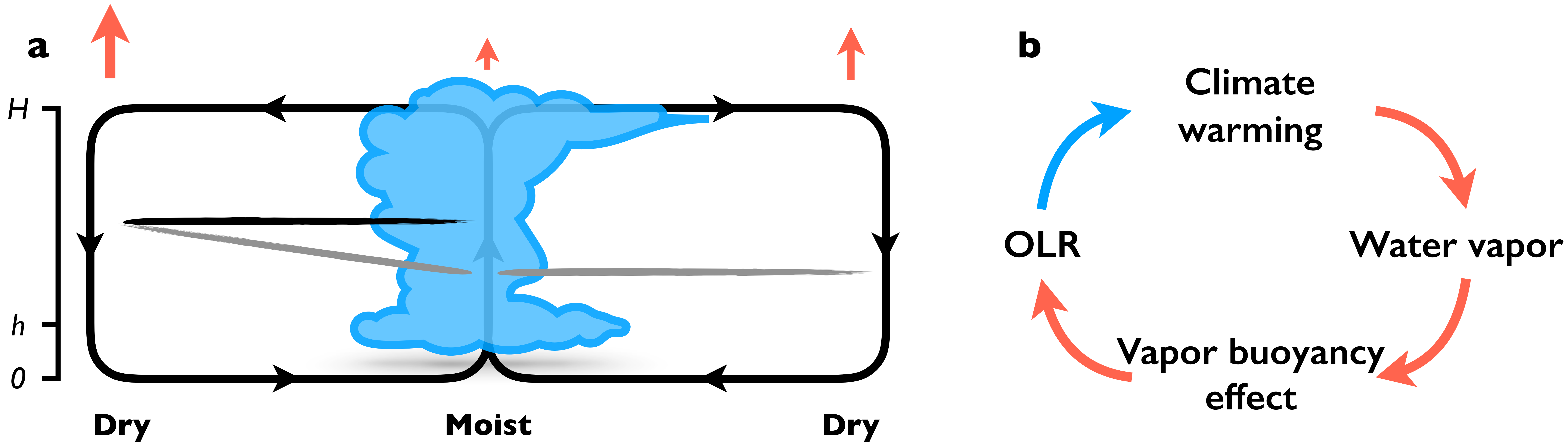


$$d\Delta OLR/dT_s \sim 0.2\ W/m^2/K$$

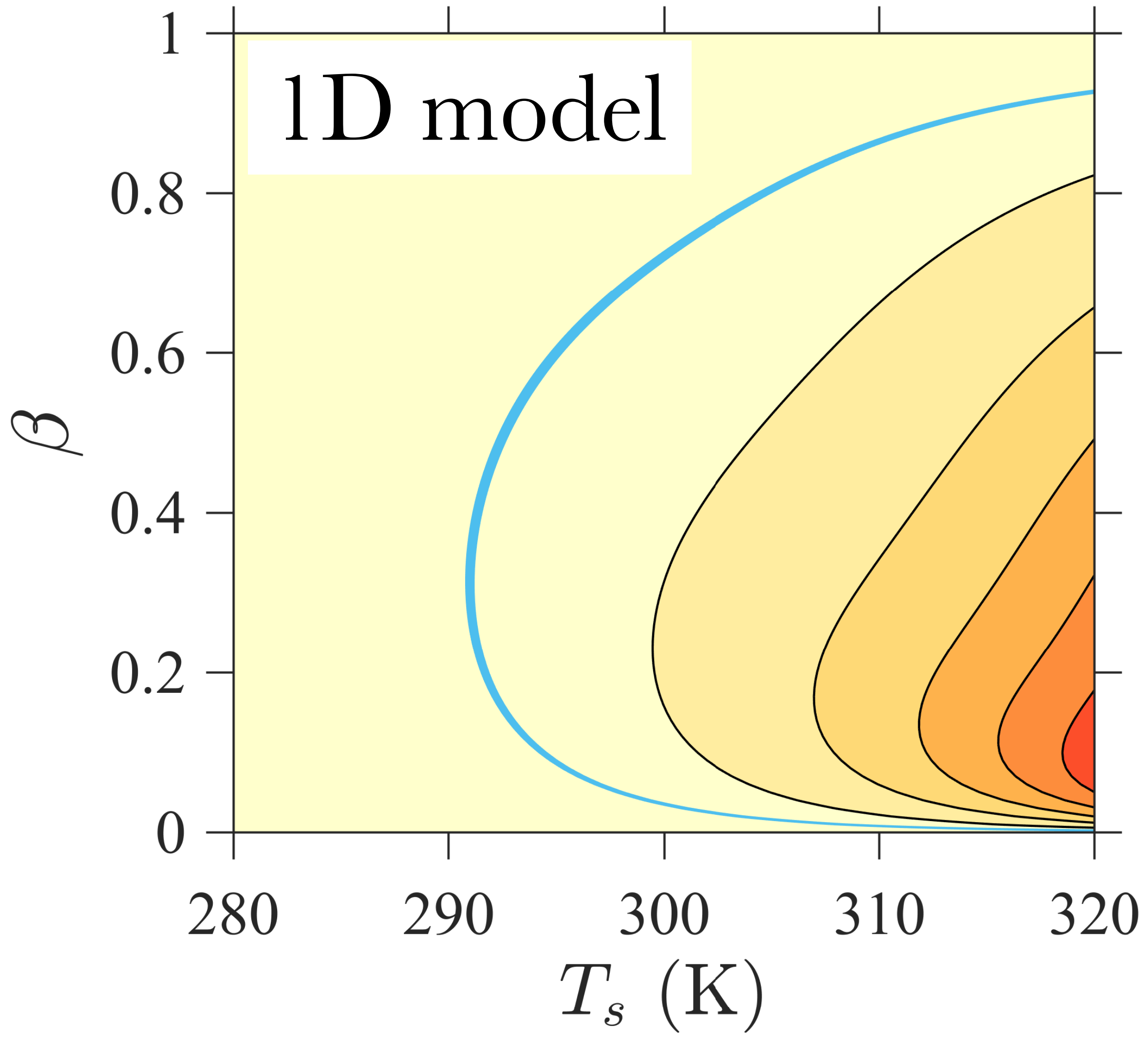
Similar to cloud or surface albedo feedbacks

Only consider the clear-sky effect

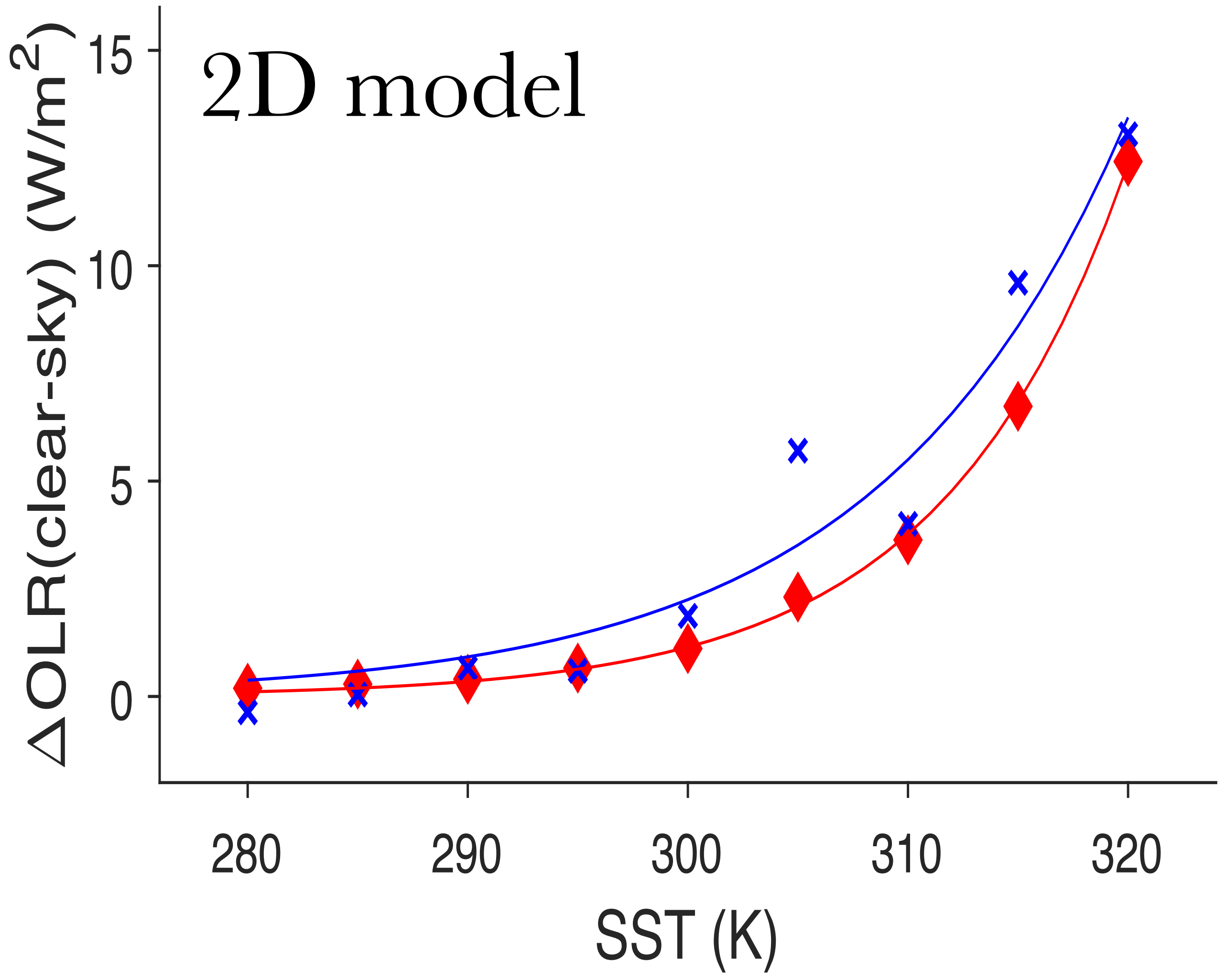
The lightness of water vapor stabilizes tropical climate



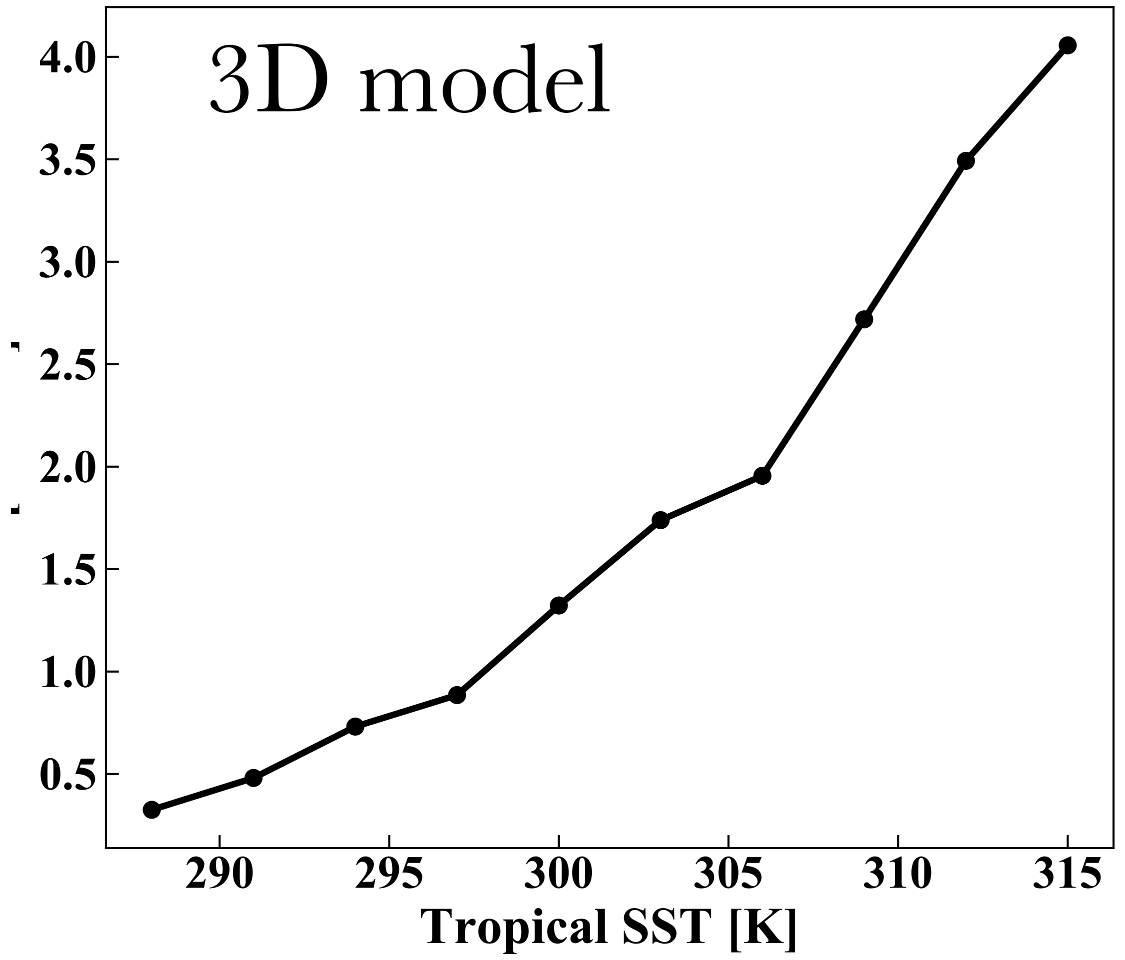
The lightness of water vapor is incredible!



Yang and Seidel 2019
10.31223/[osf.io/ha9sx](osf.io/ha9sx)

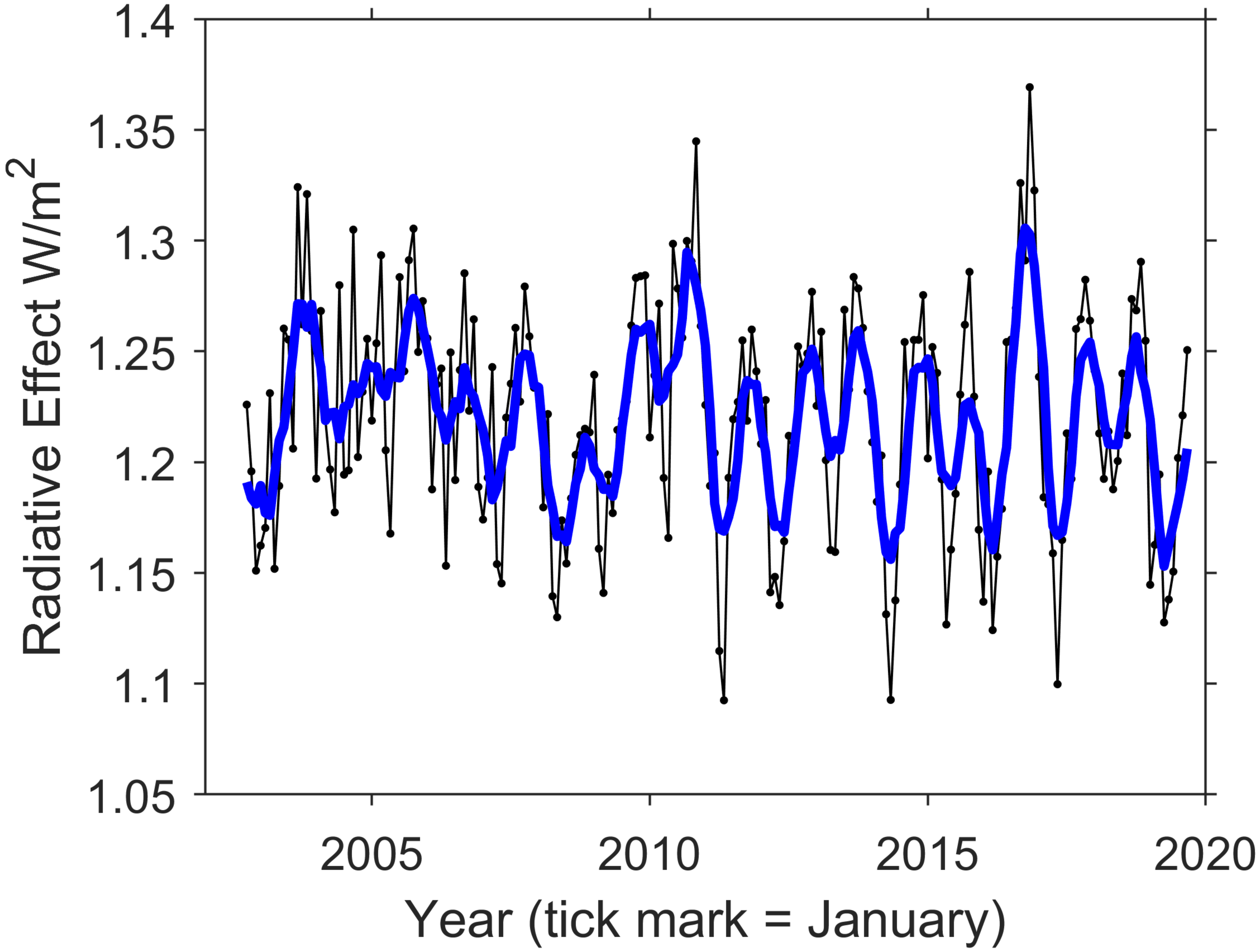


Seidel and Yang
Submitted



Zhou and Yang
In prep.

The radiative effect of vapor buoyancy is about 1 W/m²



NASA AIRS data; deep tropic

Use WBG to constrain temperature differences

Require the virtual temperature being horizontally uniform

$$T_m\left(\frac{1+r_m/\varepsilon}{1+r_m}\right)=T_d\left(\frac{1+r_d/\varepsilon}{1+r_d}\right)$$

We can solve for the temperature difference by assuming the moist column is saturated

$$\Delta T_{WBG}=T_m\left(\frac{1}{\varepsilon}-1\right)\left(r_m-r_d\right)$$

Temperature difference between the two dry columns

Note: $T_m = T_{d,noVB}$